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## PREPARATION OF PETROFABRIC DIAGRAMS

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### INTRODUCTION

So far as known to the writer no paper presenting detailed procedures for preparing petrofabric diagrams has as yet appeared in English. The fundamental methods for the investigation of rock fabrics with the aid of the universal stage were created and developed abroad by Schmidt<sup>1</sup> and Sander.<sup>2</sup> Of late petrofabric studies in this country have increased in number and variety in a most encouraging manner. Several papers describing the results obtained by petrologists here have been published. The pioneering interpretative effort was made by Knopf in 1933.<sup>3</sup> She presented a lucid discussion of the theories and objectives of petrofabric analysis as conceived by Professor Sander, and provided an excellent background concerning the concepts involved in such studies.

During the winter of 1936-37 the writer was privileged to study at the Mineralogic and Petrographic Institute of Leopold-Franzens University, in Innsbruck, Austria. He takes this occasion to thank Professor Sander for the hospitality, interest and assistance so graciously extended to him, and by his assistant Dr. Joseph Ladurner. It is the intention here to present a simplified, clear exposition of the general procedures currently used abroad in petrofabric studies. It is hoped that more petrologists will feel sufficiently encouraged to apply such methods to their particular problems. If even a modicum of interest in rock fabric investigations is aroused the writer will feel that some part of his obligation to the workers at Innsbruck will have been repaid.

A somewhat more detailed description of the general procedure than heretofore available in English will be given. Such workers as Gilluly,<sup>4</sup>

<sup>1</sup> Schmidt, Walter, Gefügestatistik: *Tschermaks Min. u. Petr. Mitt.*, vol. 38, pp. 392-423, 1925 (Festband Friedrich Becke). Also *Tektonik und Verformungslehre*, Gebrüder Borntraeger, Berlin, 1932, pp. 208.

<sup>2</sup> Sander, Bruno, *Gefügekunde der Gesteine*. Julius Springer, Vienna, 1930, pp. 352.

<sup>3</sup> Knopf, Eleanor Bliss, *Petrotectonics: Am. Jour. Sci.* (5), vol. 25, pp. 433-70, 1933.

<sup>4</sup> Gilluly, James, Mineral orientation in some rocks of the Shuswap terrane as a clue to their metamorphism: *Am. Jour. Sci.* (5), vol. 28, pp. 182-201, 1934.

Ingerson,<sup>5</sup> Bell,<sup>6</sup> Fairbairn<sup>7</sup> and others have published articles amply demonstrating the value of the statistical approach. In parts of their papers are comments and instructions on various phases of the procedure. To avoid repetition, where one of these students has amplified some particular phase of the subject here dealt with, specific references will be given. To reach as large an audience as possible, step-by-step procedures are presented, and to aid in visualization considerable illustrative material is included. Those with a foreknowledge of universal-stage technique, may, perhaps, find some of this detail of no particular interest. In such a case, the scope of the subject matter treated will, it is hoped, furnish a satisfactory guide to the preparation of petrofabric diagrams in the conventional manner.

### PREPARATION FOR MEASUREMENT

#### *Collecting the specimen*

When collecting the specimen it is necessary to note carefully the strike and dip of conspicuous structures. The specimen is first knocked off the outcrop, replaced in its original position, and the geographical coordinates of the structures determined. The strike and dip should be placed directly on the specimen whenever feasible. If the rock is not sufficiently smooth, adhesive tape can be applied and strike and dip written on in indelible pencil. Or the direction of strike and dip can be scratched on with a dental pick; the specimen number applied; and the coordinates placed in the notebook. Comments and sketches should be set down while at the outcrop so that the structural association and the particular problem involved are clearly stated.

#### *Assignment of reference axes*

According to Sander an *s*-surface may be defined as any conspicuous surface of parting such as a plane of schistosity, foliation, shear, or bedding. For convenience in reference a triaxial coordinate system is used to designate the relationships of the linear and planar structural features in a rock specimen. Axes, known respectively as "*a*," "*b*," and "*c*," are assigned with definite regard to visible rock structures wherever such are present. Thin sections are usually cut perpendicular to these axes of reference. The above mentioned axes need have no necessary relation to

<sup>5</sup> Ingerson, E., Fabric analysis of a coarsely crystalline polymetamorphic tectonite: *Am. Jour. Sci.* (5), vol. 31, pp. 161-87, 1936.

<sup>6</sup> Bell, James F., Festigkeit und Gefügeregel am Beispiel eines Granits: *Neues Jahrb. Min., Geol.*, vol. 71, BB. Abt. A., pp. 193-213, 1936.

<sup>7</sup> Fairbairn, H. W., Introduction to petrofabric analysis, 1935, pp. 142. (Issued by the Dept. of Geology, Queens University, Kingston, Canada.)



the geographical coordinates of the specimen such as strike and dip. In large part the function of the axial nomenclature is to provide a set of coordinates for correlating the fabric elements in the rock with a reference sphere used as a basis for plotting statistical results. These axes are closely analogous in function to those employed in crystallography as a basis for morphological descriptions. The attitude and disposition of such rock structures as foliation planes, joints, bedding planes, folds, faults, fractures, and directions of mineral parallelism can be readily described with the use of such axes.

The "a" axis indicates the assumed direction of relative movement or transport of material. The "a" axis lies in the *s*-surface and, together with "b," defines the plane parallel to which relative shearing movements have taken place. When there has been bodily movement of grains, or parts of individual grains, past one another, the plane of slip, or the *s*-plane, corresponds to the plane "ab." In the case of folded rocks transport and slip take place in the direction of dip of the fold.

The "b" axis is the axis of slip normal to the direction of slip "a," and perpendicular to the plane "ac." In movements which produce external rolling of one set of mineral particles with respect to another set, "b" is the axis of internal rotation. The "b" axis is the axis of folding and its direction is said to be the "tectonic strike" of the fold.

In a hand specimen the "b" axis may frequently be detected by the alignment of mineral grains visible on the *s*-surface. It may manifest itself as the axis of a fold.<sup>8</sup> Or its location may be suggested by the line of intersection of two or more shear surfaces. In selecting surfaces for thin sections the "b" axis is assumed to be the direction of conspicuous structure which is visible on the *s*-surface, i.e., in the plane "ab." Thus the "b" axis might be the direction of minute crumplings in the foliation plane of a pencil slate; the direction of parallelism of hornblende needles in the foliation plane of a gneiss; or, in a ripple-marked sandstone, the direction of the wave crests. Experience indicates<sup>9</sup> that rotation about "b" is a very frequently recurring phenomenon, and also that the "b" axis is often horizontal. Hence, as it may well be the most informative means of attack on the major fabric elements of a rock, the thin section normal to "b" is usually the first to be studied in detail.

The "c" axis is normal to the plane "ab," and, therefore, perpendicular to the *s*-surface. Axes "a" and "c" define the plane standing normal to the *s*-surface.

#### *Preparation of thin sections*

When the structures on the hand specimen have been identified and

<sup>8</sup> Knopf, E. B., *opus cit.*, p. 452.

<sup>9</sup> Sander, B., *opus cit.*, p. 59.

the axes of reference located, thin sections normal to these axes are cut as a first step toward microscopic investigation. Usually the thin section maker is not cognizant of the procedures by which the axes are selected. To obviate this difficulty surfaces to be measured are ground plane before the specimen is submitted to him. Three faces respectively perpendicular to the axes of reference are usually ground on the specimen. Arrows, and other distinguishing marks, in India ink, are placed on these surfaces, parallel, or sometimes perpendicular, to the direction of the structures visible on the surface. Before the section is cut it is well to make a simple sketch of the hand specimen showing the general outlines, the trace of the structures, the location of the ground surfaces, arrows and other symbols. The thin section preparator should be instructed that the

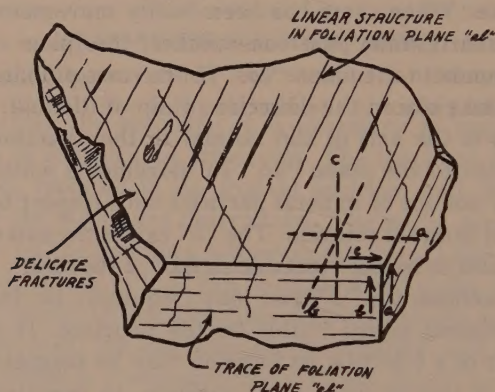


FIG. 1. Sketch of a specimen of gneiss with three perpendicular faces ground ready for sectioning.

section is to be made directly from the marked, ground surface by cementing the object glass to that surface. The ground surface should be marked in such a manner as to indicate the approximate dimensions and outlines of the completed section. If the ground surface has a straight edge, or if a definite line of direction is visible on the surface, the straight edge must be preserved if possible, and the direction line set parallel to the edge of the object glass. All direction marks and symbols on the ground surface must be transferred to the object glass with a diamond point in exact correspondence with those on the specimen. The number of the specimen and the orientation of the section must also be permanently and clearly marked on the object glass.

The place on the specimen from which the section was cut should be marked by the section maker so that the specimen and the rock slice can be correlated. For most purposes sections should be ground as thin as possible. The rock slice should be embedded in well-cooked balsam



because of the danger of mashing or twisting the slice if the segment mount is accidentally screwed down too far. All remaining pieces of the hand specimen should be returned. If any of these precautions are neglected considerable trouble in orientation may ensue and erroneous results be obtained. Ingerson<sup>10</sup> has recently designed a helpful apparatus for setting up the specimen according to its geographical coordinates; obtaining the coordinates of structure planes; and accurately orienting the thin section.

#### SUPPLEMENTARY OBSERVATIONS TO BE MADE DURING MEASUREMENTS

As designated by Ingerson there are, in general, two major types of diagrams, *elemental* and *collective*. He states: "*Elemental* diagrams are units that are combined to form other diagrams known as *collective* diagrams." And: "A *collective* diagram is prepared by collecting the points from a number of similar elemental diagrams, commonly from the same thin section, into a single diagram." He also establishes a class of diagrams called *partial* diagrams "which are elemental diagrams that have been prepared by a definite selection of grains."<sup>11</sup>

In the very beginning a large scale drawing of the thin section is made so that the areas covered in each traverse can be re-located at will. In examining the thin section, both before and during measurement, care should be taken to note any other visible evidences of orientation present in addition to the well defined structural features selected as the basis for locating the axes of reference. Whenever such structures are found, separate detailed measurements of them should be made. In this way structures which at first appear subordinate may eventually be found to be of basic importance. The need for additional partial diagrams of subdued features very frequently becomes evident only after many grains have been measured. Sometimes only the finished diagram will indicate emphatically the presence of structures which have otherwise eluded search. When fabric elements are thus revealed, new thin sections may have to be cut and additional measurements made.

If any concentration of poles becomes evident on the elemental diagrams, the thin section and the hand specimen should be studied and compared to detect such superficial manifestations as may be present. The fundamental purpose in making a diagram is not solely the production of the contoured diagram itself, although the latter is of unquestionable value for comparison and depiction of the internal grain

<sup>10</sup> Ingerson, E., Accurate orientation of thin sections: *Am. Mineral.*, vol. 22, pp. 760-72, 1937.

<sup>11</sup> Ingerson, E., Fabric analysis of a coarsely crystalline polymetamorphic tectonite. *Am. Jour. Sci.* (5), vol. 31, pp. 171-72, 1936.

relationships. During plotting, elusive fabric elements may become manifest through the grouping or localized concentration of poles. Such indications suggest the presence of hidden features which should be thoroughly investigated. Only in this way can the sequence of movements and the developmental history of the rock be determined.

During measurement, as elemental diagrams are made, grains with notable features as, for example, textural variation or alternation; unusual internal structures; suggestive distribution with respect to particular minerals; or distinctive boundary relations, should be indicated by the use of different pole symbols. Possibly quartz grains in contact with tourmaline, or those poeciloblastic with respect to garnet might be singled out by using special symbols for the poles of grains with such distribution. Quartz grains in contact with muscovite, as compared with those in contact with grains of calcite, might be tentatively distinguished by separate pole symbols. In a mylonitized rock, grains of quartz in contact with the original feldspars could be designated in a different manner from quartz grains in the surrounding mesostasis of the rock. By such selective plotting significant organization of the grains can be detected *as measurement proceeds*.

#### *Axes of the universal stage*

To ascertain the nature of a rock fabric, according to the fundamental methods developed by Sander and Schmidt, the position in space of the optic axis of each measured grain of the selected mineral must usually be determined. Methods for the identification of uniaxial minerals with the universal stage have been given by Berek<sup>12</sup> and Reinhard<sup>13</sup> and others. But their instructions are primarily for determining the form of the indicatrix as a basis for distinguishing uniaxial from biaxial minerals. The procedure for measuring the optical orientation of uniaxial minerals of known identity can be reduced to a definite routine. Fairbairn<sup>14</sup> has given a procedure for measuring the optical orientation of uniaxial minerals. His treatment of this subject seems to presuppose a rather broad familiarity with universal-stage methods in general. Unfortunately instruction in the use of this instrument is, at present, not nearly so widespread as might be desired.

The procedures here given, though simplified, are believed to be suitable as an outline of the essential technique. Certain minor steps in manipulation, which may be dispensed with when the general orientation

<sup>12</sup> Berek, Max, *Universaldrehtischmethoden*, Gebrüder Borntraeger, Berlin, 1924, pp. 64-65.

<sup>13</sup> Reinhard, Max, *Universaldrehtischmethoden*, B. Wepf e Cie, Basel, 1931, pp. 18-21, 23-24.

<sup>14</sup> Fairbairn, H. W., *opus cit.*, pp. 17-18.



of the crystal is firmly in mind, have been included. It is believed that a general knowledge of the optics of uniaxial crystals will be found a sufficient basis for understanding the various steps.

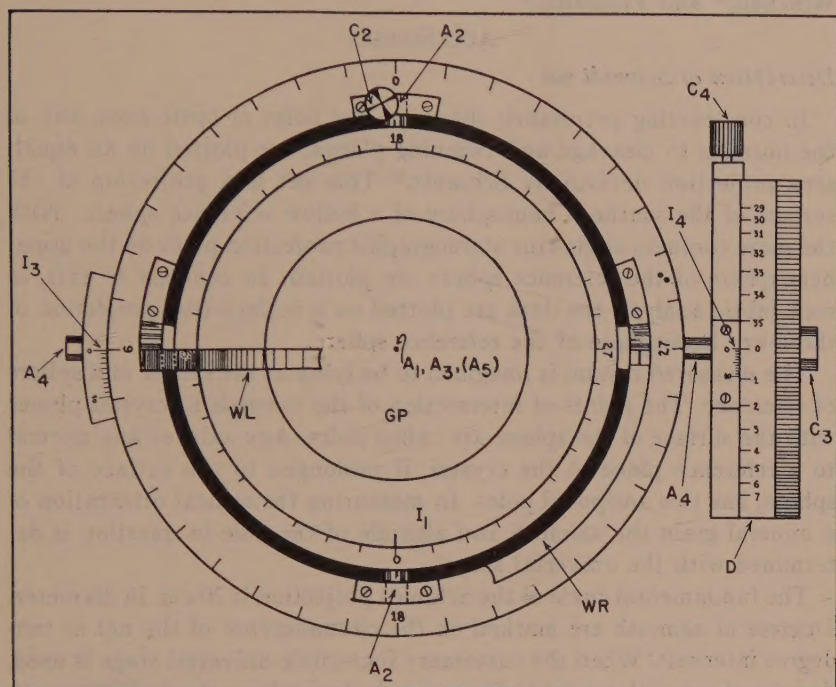


FIG. 2. Diagram of a standard 4-circle universal stage.  $A_1$ ,  $A_2$ ,  $A_3$ ,  $A_4$ , and  $A_5$  (microscope axis)=the several axes;  $C_2$ ,  $C_3$ ,  $C_4$ =the arresting screws of axes  $A_2$ ,  $A_3$ ,  $A_4$  respectively;  $I_1$ ,  $I_3$ ,  $I_4$ =the indices of axes  $A_1$ ,  $A_3$ ,  $A_4$ ;  $D$ =calibrated drum of  $A_4$ ;  $GP$ =the glass plate;  $WL$  and  $WR$ =calibrated arcs of  $A_2$ , left (erect) and right (reclining).

The various axes of the 4-circle universal stage are here designated according to the system of Berek.<sup>15</sup>

Axis  $A_1$ : The axis of rotation of the innermost ring which supports the glass plate, thin section, and segments. This axis is at all times the direction of the normal to the thin section. Axes  $A_1$  and  $A_2$  form the first pair of mutually perpendicular axes. (See Fig. 2.)

Axis  $A_2$ : The north-south horizontal axis.

Axis  $A_3$ : The vertical axis of the outer circle of the universal stage. The  $A_3$  axis coincides with the microscope axis when the stage is in proper adjustment. Axes  $A_3$  and  $A_4$  form the second pair of mutually perpendicular axes.

Axis  $A_4$ : The east-west horizontal axis. This axis is controlled by the large graduated drum.

Axis  $A_5$ : The axis of the object stage of the microscope, and, therefore, coincident with the microscope axis.

<sup>15</sup> Berek, Max, *opus cit.*, pp. 9-11.

Detailed instructions for mounting and adjusting the universal stage cannot be given here. The reader is referred to the standard texts of Berek,<sup>16</sup> Reinhard,<sup>17</sup> and Nikitin,<sup>18</sup> and to the works of Emmons,<sup>19</sup> Winchell,<sup>20</sup> and Fairbairn.<sup>21</sup>

#### ACCESSORIES

##### *Description of Schmidt net*

In constructing petrofabric diagrams the poles of optic axes, and of the normals to cleavage and twinning planes, are plotted on an equal-area projection devised by Schmidt.<sup>22</sup> This net is a projection of the surface of the southern hemisphere of a hollow reference sphere. With the more common angle-true stereographic projection poles on the upper hemisphere of the reference sphere are plotted. In contrast to this, in rock fabric analysis the data are plotted on a surface-true projection of the lower hemisphere of the reference sphere.

The measured crystal is imagined to be lying at the center of a sphere of reference. The points of intersection of the normals to crystal planes with the surface of the sphere are called poles. Any axis, or any normal to a reference plane in the crystal, if prolonged to the surface of the sphere, has two antipodal poles. In measuring the optical orientation of a mineral grain the azimuth and altitude of the pole in question is determined with the universal stage.

The fundamental circle of the Schmidt projection is 20 cm. in diameter. Degrees of azimuth are marked on the circumference of the net at ten-degree intervals. When the customary four-circle universal stage is used, degrees of azimuth are laid off counterclockwise from the 0-degree mark (south point) on the net circumference. The figures then run in the same order as the calibrations on the graduated circle of  $A_1$ . Arcs of inclined great circles at 2-degree intervals are projected on the net. All these great circles pass through the equatorial plane of the reference sphere along a diameter whose trace on the net is the 0–180° meridian. The arcs of vertical small circles are also projected at 2-degree intervals. In this way interpolation during construction and rotation is made practicable. The fundamental circle of the net is itself the projection of the circumference of the equatorial plane of the reference sphere, i.e., the only possible horizontal great circle. The north-south diameter (0–180°

<sup>16</sup> Berek, Max, *opus cit.*, pp. 31–39.

<sup>17</sup> Reinhard, Max, *opus cit.*, pp. 37–45.

<sup>18</sup> Nikitin, W., *Die Fedorow-Methode*, Gebrüder Borntraeger, Berlin, pp. 15–27, 1936.

<sup>19</sup> Emmons, R. C., In "Microscopic Characters of Artificial Minerals" by A. N. Winchell, p. 144, 1931.

<sup>20</sup> Winchell, A. N., *Elements of Optical Mineralogy*, pp. 225–27, 1931.

<sup>21</sup> Fairbairn, H. W., *opus cit.*, pp. 14–15.

<sup>22</sup> Schmidt, Walter, *opus cit.*, pp. 395–96.







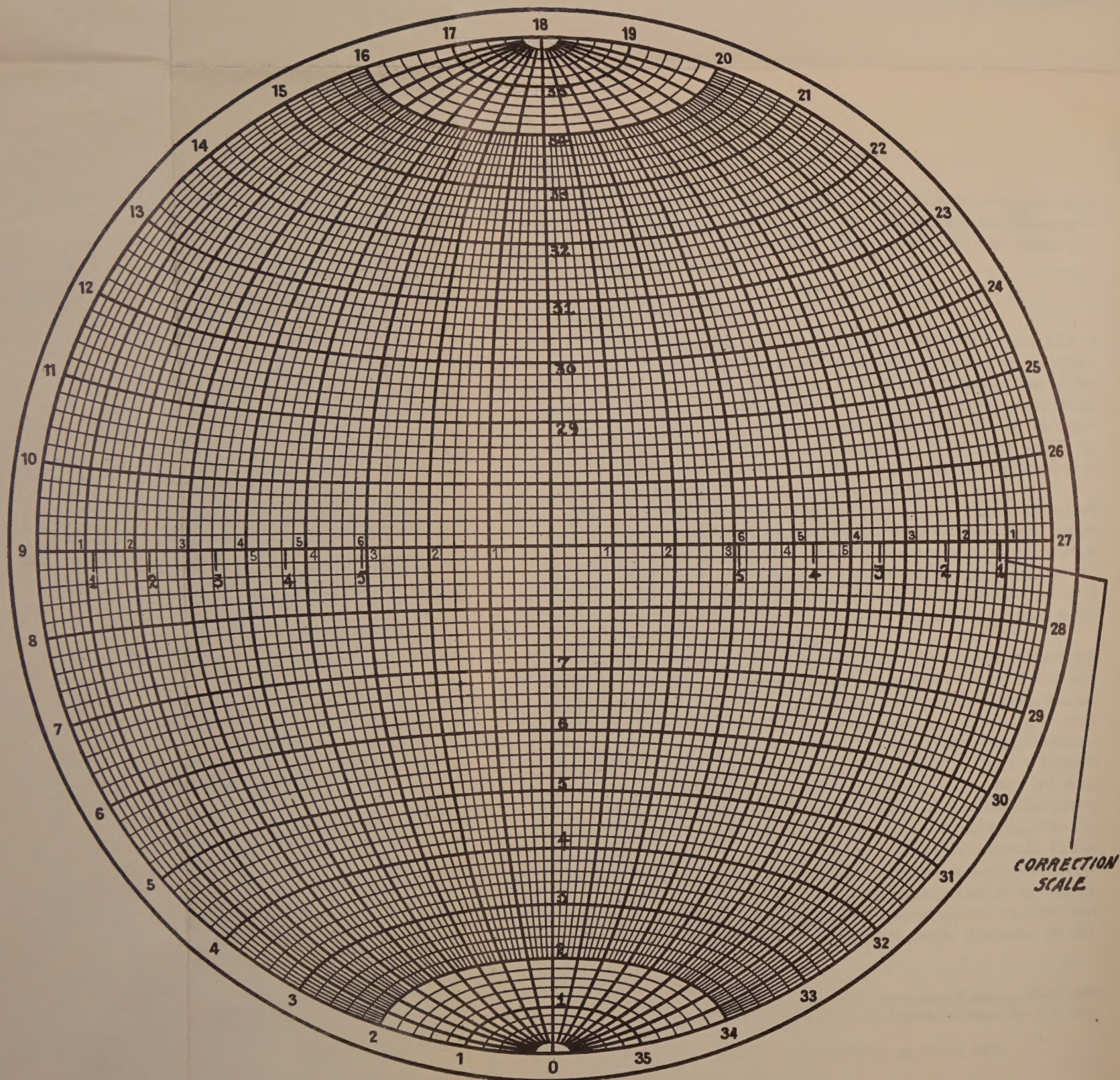


FIG. 3. Schmidt net showing the various scales used in plotting.



meridian) of the projection is the trace of the vertical great circle which passes through the north and south poles of the reference sphere. The east-west diameter ( $90-270^\circ$  meridian) is the trace of the largest possible vertical small circle, which is a limiting case and at the same time a great circle.

On the prepared Schmidt nets there are two sets of figures lying along the east-west diameter. The dotted figures below the east-west diameter begin at the center and increase to right and left. When quartz or calcite are measured this set of figures is used to plot the poles of optic axes when the latter are brought into coincidence with the microscope axis. Two other groups of figures begin at the east and west points on the circumference and increase toward the center. These are used, when quartz is measured, for plotting the pole after the optical equator is brought parallel to the microscope axis. Two other groups of figures, beginning at the east and west points should be placed along this diameter. They are used when plotting the optic axes of calcite crystals after the optical equator has been brought parallel to the microscope axis. They furnish the necessary angular corrections due to the difference in refractive index between the "e" rays of calcite (1.486) and that of the segments (1.64 approx.). These corrections can be obtained from the nomogram of Berek,<sup>23</sup> or from the diagram of Emmons.<sup>24</sup> The net here reproduced shows the positions of the correction figures accurately enough so that they may be transferred from the illustration if desired (Fig. 3).

Two sets of figures should be placed beside the north-south meridian. Beginning from the  $180^\circ$  point on the circumference the figures 36 (usually omitted), 35, 34, 33, etc., in descending order toward the center are plotted. From the  $0^\circ$  figures 0 (usually omitted), 1, 2, 3, etc., in ascending order toward the center are set down. These figures correspond to the calibrations on the drum of  $A_4$ . They are used when plotting the poles of the normals to twinning and translation planes in calcite after the trace has been brought into the east-west position. They are also used for plotting the pole when the cleavage trace of a mica crystal is brought parallel to the east-west crosshair.

#### *Schmidt sledge and its use*

Usually, for statistical purposes, an insufficient number of grains are encountered in a single traverse, even in a rock of relatively fine grain. A number of successive traverses must then be made across the section. For valid results, in any given set of measurements, all traverses should be parallel to the selected structural line of reference. It is hardly possible

<sup>23</sup> Berek, Max, *opus cit.*, p. 57 and Table I.

<sup>24</sup> Emmons, R. C., A modified universal stage: *Am. Mineral.*, vol. 14, p. 450, 1929.

to move the section straight across the universal-stage platform and preserve identical orientation without mechanical aid. To assist in keeping the section properly oriented, Schmidt designed a "*Parallelführer*" or guide, sometimes called a "sledge." This is a right-angled metal bracket which is attached to the upper segment mount. One arm of the sledge fits into a north-south channelway on the upper surface of the

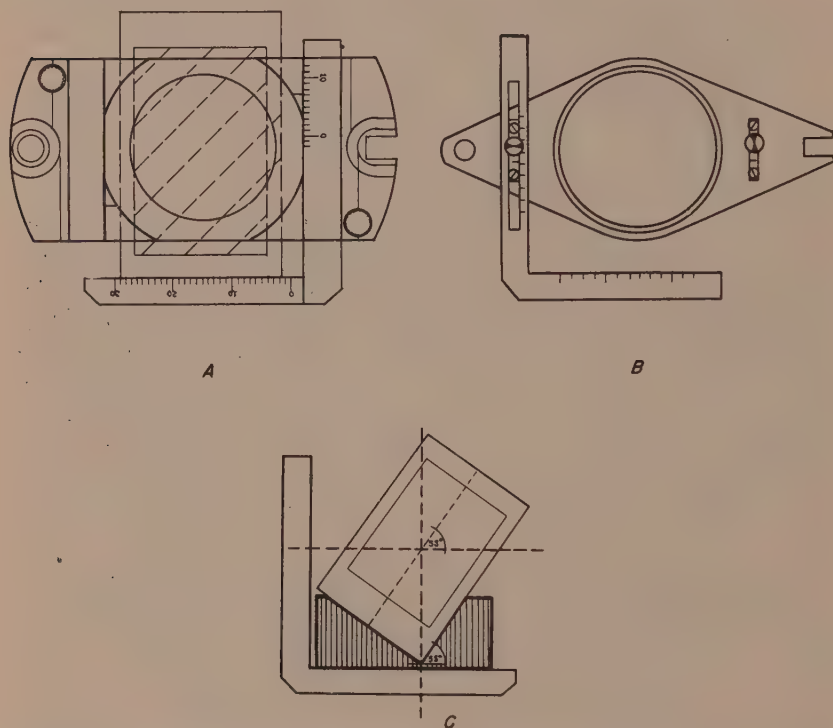


FIG. 4. A. Type of segment mount which can be purchased already slotted for use with the Schmidt sledge.

B. Ordinary segment mount adapted for use with the sledge.

C. Sketch illustrating use of celluloid angle plates employed in making an oblique traverse.

mount. The other arm, against which the section rests and by means of which it is guided, projects beyond the mount and extends east-west. There are several types of segment-mounts in use at present. Two of these are illustrated. If the segments at hand are not fitted for using the guide, they can be readily adapted (Fig. 4A and B).

The section is moved along the guiding edge with the fingers, each grain measured being centered as well as possible. The arm by which the



sledge is attached to the segment mount can be moved up or down and firmly fixed in position. By adjustment of this arm a different line of section can be examined each time. So long as the lower edge of the thin section is held firmly against the east-west arm of the sledge, successive parallel traverses are obtained.

To examine a sufficiently large area of the thin section, it may be necessary to cut off part of the object glass. If this is done care must be taken to cut squarely across the preparation exactly at right angles to the long direction of the object glass. Otherwise, when mounted, the section will lie askew and subsequent traverses will not be parallel to the earlier ones.

Structures of the rock fabric which make an angle with the edge of the thin section must often be traversed. To investigate them the section must be crossed obliquely. This is often very difficult because of the small range through which the section may be tipped, and because appreciable lateral displacement is prohibited due to interference with the studs holding the segment mount. If, when the section is tipped, even a small part of the object glass projects beyond the inner circle of the stage, measurement is greatly restricted. It is often impossible to proceed without beveling the object glass. In such cases a corner is cut off so as to make a sufficiently long bevel to prevent the section from rocking when laid against the sledge. Using celluloid or thin metal guides, into which notches have been cut, it is sometimes feasible to measure without trimming the section (Fig. 4C). Whether the object glass is beveled, or accessory guides employed, care must be taken to check the orientation of the section frequently during measurement.

#### MEASUREMENT OF UNIAXIAL MINERALS WITH THE UNIVERSAL STAGE

After the thin section has been properly mounted every grain of the selected mineral encountered in the traverses should be measured if feasible to do so. It may happen that the observed crystal is at extinction after centering. It is then necessary to determine whether the optic axis coincides with the microscope axis, or whether it lies, fortuitously, parallel to one of the vibration directions of the microscope. If, now, the section is rotated by turning about  $A_5$  and the crystal becomes illuminated, then the optic axis does not coincide with the microscope axis. It is, therefore, either inclined to, or lies in, the plane of the section. In the following discussion, after the crystal has been adjusted so that the optic axis coincides with the microscope axis, the grain is said to be in the *polar position*. If some diameter in the equatorial plane of the indicatrix is brought into coincidence with the microscope axis, the crystal is said to be in the *equatorial position*.

*Measurement when optic axis is inclined to the plane of the section*

We will assume that the crystal is illuminated after centering. The measured grain is known to be uniaxial, and is, let us say, quartz. Starting from the rest position:

E 1a. Rotate about  $A_1$  and bring the grain to a position of extinction. (In the following, essential steps are designated "E.")

Since the crystal is at extinction the optic axis lies parallel to the plane of vibration of either the polarizer or analyzer. But it is not known whether the optic axis is parallel to the north-south or to the east-west vibration plane. Nor is it known whether the optic axis is parallel, or inclined, to the plane of the section. To distinguish these two cases:

E 2a. Rotate a few degrees about  $A_2$ .

If the crystal becomes illuminated the optic axis is inclined to the plane of the section and parallel to the north-south crosshair. If the crystal remains at extinction, refer to step "1b" in the following section on measurement when the optic axis lies in the plane of the section.

E 3a. Return to the 0-degree position on  $A_2$ .

To verify the north-south position of the optic axis:

4a. Rotate a few degrees on  $A_4$ .

The grain should now remain at extinction, if the optic axis extends north-south. If the crystal is in this position its orientation cannot be measured. For when the section is rotated about  $A_2$  it becomes illuminated, and if then rotated about  $A_4$  it remains illuminated. Hence it is impossible to bring the crystal from a position of illumination to one of extinction. Therefore:

E 5a. Rotate the section 90 degrees on  $A_1$  to the next position of extinction.

The optic axis should now lie east-west parallel to the  $A_4$  axis. To verify this:

6a. Rotate a few degrees on  $A_2$ , ascertain that the crystal remains dark, and return to the 0-degree position on this axis. As an additional check one may:

7a. Rotate a few degrees on  $A_4$ .

Since the optic axis is inclined to the plane of the section (as determined in 2a), the grain will become illuminated. To determine the coordinates of the optic axis:

E 8a. Rotate, forward or backward, about 30–35 degrees on  $A_4$ , leaving the stage in this position.

E 9a. Rotate, right or left, on  $A_2$  and bring the crystal to extinction.

E 10a. Rotate back to the 0-degree position on  $A_4$ .

The crystal will now be in either one of two positions depending on



the original inclination of the optic axis with respect to the plane of the section. Either the optic axis coincides with the microscope axis, or some diameter in the plane defined by the horizontal crystallographic axes (the "equatorial plane" of the indicatrix) coincides with the microscope axis. In this latter case the optic axis coincides with axis  $A_4$ . Before the pole can be plotted, it is necessary to distinguish between these two positions. This is done by:

E 11a. Rotating about  $A_5$ .

If the optic axis coincides with the microscope axis, the crystal will remain at extinction. If some diameter in the equatorial plane of the indicatrix lies in the observation direction, the crystal becomes illuminated. The procedures for plotting the pole of the optic axis is different in each case and separate directions are given later.

*Measurement when the optic axis lies in the plane of the section or nearly so*

If in step 2a the crystal remains at extinction, the optic axis is either inclined to the plane of the section and lies parallel to the east-west vibration plane, or it lies in the plane of the section, or nearly so. To distinguish these two positions and to determine any slight deviation of the optic axis from the horizontal:

E 1b. After returning to the 0-degree position of the  $A_2$  axis (step 3a), rotate about  $A_4$ .

If the grain remains at extinction after rotation about both  $A_2$  (step 2a) and  $A_4$  (step 1b), the optic axis lies in the plane of the section or very nearly so. Then:

E 2b. Return to the 0-degree position on  $A_4$  and proceed with step 3b.

(Note: If the optic axis is inclined to the plane of the section and lies east-west, the crystal will become illuminated when rotated about  $A_4$  in step 1b. In this case return to the 0-degree position on  $A_4$  and proceed with step 8a above.)

The equatorial plane of the indicatrix is perpendicular to the optic axis. When the optic axis lies in the plane of the section the equatorial plane is vertical and some diameter in this plane coincides with the microscope axis. If, then, the optic axis is brought parallel to one crosshair, the trace of the equatorial plane coincides with the other. Then, upon rotation about both  $A_2$  and  $A_4$  from the rest position the crystal will remain at extinction. Having determined in 1b that the optic axis lies in the plane of the section, or nearly so, the next step is to ascertain whether the axis is parallel to the east-west or north-south crosshair. Verify that axes  $A_2$  and  $A_4$  are at their 0-degree position; then:

E 3b. Rotate a few degrees about  $A_2$ . Leaving the inner stage in this position

E 4b. Rotate about  $A_4$  and return to the 0-degree position of this axis. If the grain remains dark the optic axis lies north-south and the crystal is in the wrong position for measurement. If the axis lies north-south, proceed with step 6b. If the crystal becomes illuminated, proceed with step 7b. In either case to avoid confusion first:

E 5b. Rotate back to the 0-degree position of  $A_2$ .

E 6b. Rotate 90 degrees on  $A_1$  to the next position of extinction and bring the optic axis east-west.

E 7b. Rotate approximately 15–20 degrees on  $A_2$ .

E 8b. Rotate on  $A_4$ , forward or backward, far enough to bring the crystal to the position of maximum illumination.

E 9b. Rotate back on the  $A_2$  axis and bring the grain to extinction.

In so doing some diameter in the equatorial plane of the indicatrix is brought into coincidence with the microscope axis. The optic axis should now coincide with  $A_4$ .

E 10b. Rotate back to the 0-degree position on the drum of  $A_4$  and take the readings.

To verify that the optical equator stands vertical:

E 11b. Rotate about  $A_5$ .

If the grain becomes illuminated, an equatorial position was secured, as should be the case. Since the "optical equator," defined by the horizontal crystallographic axes, is normal to the optic axis, when the orientation of this plane is known the pole of the optic axis can be plotted.

*Measurement when the optic axis is coincident, or nearly so, with the microscope axis*

If the grain was dark when first centered and remained at extinction upon rotation about  $A_5$ , the optic axis coincides in direction, or nearly so, with the microscope axis. When the crystal is thus oriented, it is difficult to decide whether the observed extinction is complete or partial. It is often helpful to move the optic axis a few degrees off the vertical, bring it back, and to note as carefully as possible the moment of extinction as the crystal is brought from a position of illumination. To do this:

E 1c. Rotate approximately 15–20 degrees about  $A_2$ .

E 2c. On  $A_4$  rotate a few degrees forward or backward. The grain becomes illuminated.

E 3c. Rotate back on  $A_2$  searching as carefully as possible for the actual position of complete extinction.

E 4c. Return to the 0-degree position on the drum of  $A_4$ . If it is desired to verify the orientation:

5c. Rotate about  $A_5$ .

If the optic axis has been properly adjusted into coincidence with the



microscope axis, the grain will now remain at complete extinction through a rotation of 360 degrees.

### PLOTTING

Assembly: A circle 20 cm. in diameter is inscribed on a sheet of thin transparent paper. The tracing paper is superposed on the Schmidt net so that the center of the circle coincides with the center of the projection. The tracing paper is then fastened to the center of the net with a pin so that the sheet can rotate freely. An arrow is placed on the circle drawn on the tracing paper exactly over the 0-degree point on the net circumference.

Plotting when a polar position is obtained:

1. Rotate the tracing paper until the arrow lies at the point on the circumference of the net corresponding to the reading of  $A_1$  (Fig. 5B).
2. Along the east-west diameter of the net *count out from the center* the number of degrees of rotation about  $A_2$  and plot the pole.

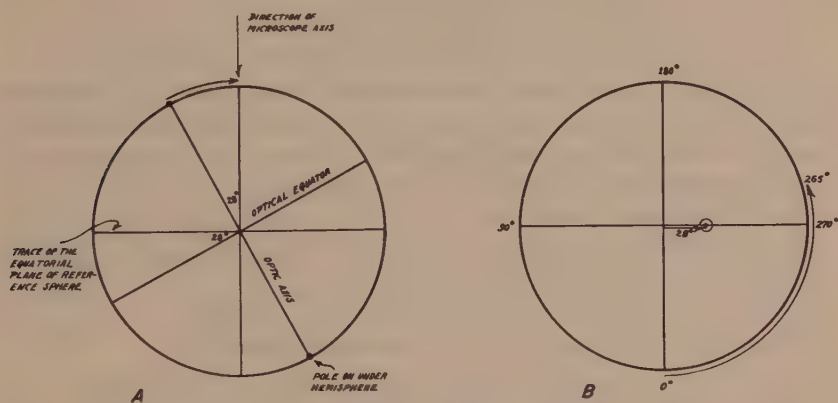


FIG. 5. Polar Position. Coordinates  $A_1$ :  $265^\circ$ ,  $A_2$ :  $28^\circ$ L.

A. Relationship of indicatrix and reference sphere.

B. Diagram illustrating method of plotting pole of optic axis.

If for example, the  $A_2$  reading is taken from the left arc of  $A_2$ , the optic axis is inclined from left to right (Fig. 5A). Only poles on the lower hemisphere of the reference sphere are plotted. Hence when the optic axis is so inclined, the pole of the lower extremity is plotted on the right side of the net. Conversely, if the optic axis is inclined from right to left, i.e., its inclination is read off the right arc, the pole is plotted on the left side of the net.

Plotting when an equatorial position is obtained:

1. Rotate the tracing paper until the arrow lies at the point on the net circumference corresponding to the reading of  $A_1$ .

2. Along the east-west diameter *count in from the circumference* of the net the number of degrees of rotation upon  $A_2$  and plot the pole (Fig. 6B).

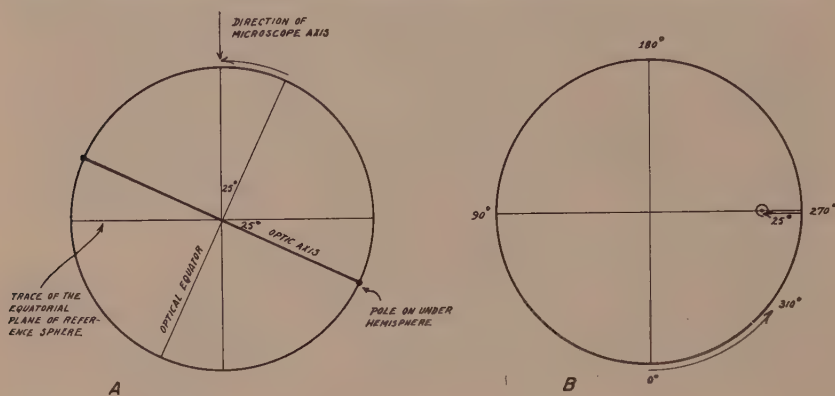


FIG. 6. Equatorial Position. Coordinates  $A_1$ :  $310^\circ$ ,  $A_2$ :  $25^\circ R$ .

A. Relationship of indicatrix and reference sphere.

B. Diagram illustrating method of plotting pole of optic axes.

If, for example, the  $A_2$  coordinate is read off the right arc, the optical equator is inclined from right to left. The optic axis, being normal to the optical equator, is therefore inclined from left to right (Fig. 6A). Its pole on the under hemisphere is plotted on the right side of the net. If, having secured an equatorial position, the degrees of rotation are read from the left arc, the pole of the optic axis is plotted on the left side of the net.

## CONSTRUCTING THE PETROFABRIC DIAGRAM

### *Making the collective diagram from elemental diagrams*

To derive the contoured diagram, poles plotted on the individual elemental diagrams are transferred to one sheet of tracing paper.

Assembly: Prepare a sheet of tracing paper with a circle 20 cm. in diameter and place an index mark (an arrow perhaps) on the circumference. One of the elemental diagrams is fastened to the drawing board. The prepared sheet of tracing paper, which later becomes the collective diagram, is superposed so that its center coincides with that of the elemental diagram. The index mark on the superposed sheet is brought into coincidence with the index mark of the underlying diagram. The two sheets are firmly fastened down together so that they cannot shift relative to one another.

Procedure: On the upper sheet a dot is placed over each pole on the diagram beneath. When all points are transferred, this elemental diagram



is removed and another substituted. The same upper sheet is again centered and its index mark brought into coincidence with that of the diagram now underneath. All poles on the second diagram are transferred as before. When all poles on each elemental diagram are transferred to this one piece of tracing paper the collective diagram is complete.

*Determining the percentage distribution of poles on the collective diagram*

A piece of millimeter cross-section paper about  $40 \times 40$  cm. square; another sheet of tracing paper; and two celluloid counting templates are now required. The coordinate paper should have heavy centimeter lines so that the counting devices can be easily centered. The dimensions of the counting device are dictated by the following considerations. To make a finished diagram, contours are drawn through points about which are distributed a certain number of poles. The number of poles assigned to each point of reference on the coordinate paper represents a definite percentage of the total number of grains measured. The diameter of the projection upon which poles are plotted is 20 cm. A circle 2 cm. in diameter and hence equal in area to  $1/100$ th of the area of the projection is of exceptional convenience for working with percentages.

One simple type of template is made by inscribing a circle 2 cm. in diameter on a small sheet of celluloid or cardboard and cutting out the circle (Fig. 7A). If only relatively few poles have been plotted, templates with areas equal to 2, 3, 4, etc. per cent of the projection can be used if desired, but the 1 per cent counter will usually be found satisfactory.

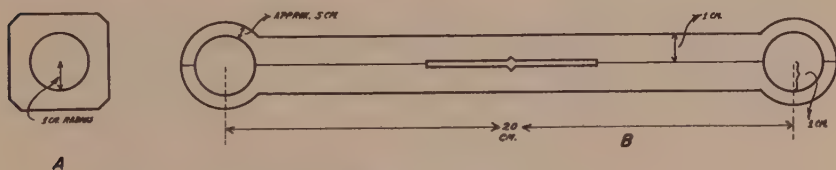


FIG. 7. Counting templates.

A. Small one per cent template.

B. One per cent perimeter counter.

For determining percentage distributions on and near the circumference of the diagram a perimeter counter spanning the 20 cm. circle is used. This device can be cut from a  $3 \times 23$  cm. strip of celluloid. A fine line is inscribed down the middle of the strip. Toward each end, 10 cm. from the center, circles 2 cm. in diameter are inscribed and the discs punched out. Along the central line, for 3 or 4 cm. on both sides of the middle point, a narrow strip approximately 2 mm. wide is cut away. A notch is then cut at the middle point so that the counter can be placed over a pin and rotated freely (Fig. 7B).

**Assembly:** The sheet of coordinate paper is fastened to the drawing board. Over this the collective diagram is placed and centered, near the middle of the sheet, over one of the intersections of the heavy centimeter lines. For simplicity the collective diagram may be turned so that its index mark lies at the south point, i.e., nearest the observer. A sheet of tracing paper, upon which a circle 20 cm. in diameter has been inscribed, is laid over the collective diagram. The center of the circle of the uppermost sheet is brought into coincidence with the center of the collective diagram. A pin, later used when intersections near the circumference are numbered, is put through the center of the assembly. An index mark is placed on the circumference of the circle on the topmost sheet over the index on the collective diagram beneath. The properly oriented assembly is securely fastened down.

**Counting the percentage distribution of poles:** There are three variations in the method of counting depending upon which part of the contour diagram is being prepared.

*A. When the area enclosed by the template lies entirely within the circumference of the contour diagram circle*

The small template is centered over an intersection of the heavy centimeter lines. This is easily done by placing it so that any four of the heavy lines, defining a  $2 \times 2$  cm. square, are tangent to the template

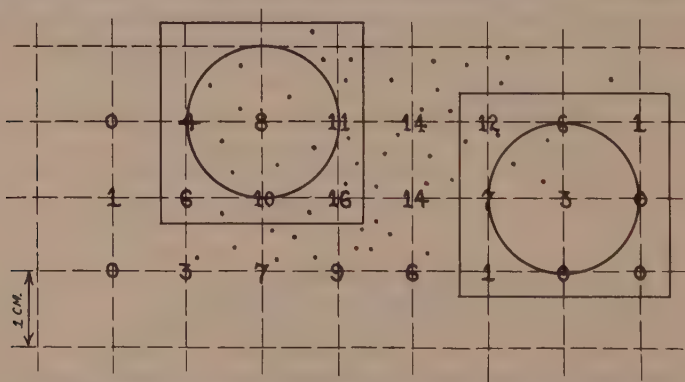


FIG. 8. Diagram illustrating the use of the counter for determining the number of poles per unit of area.

circle. Count the number of points on the collective diagram which lie within the area exposed in the template circle. Write down this number in pencil over the intersection point at the center of the template circle (Fig. 8). This procedure is followed until all centimeter intersection points, whose position is such that the area included in the template lies entirely within the net circumference, are numbered.



B. *When part of the area exposed in the counting template lies outside the circumference*

Case 1. The intersection point of the centimeter lines lies within the circumference, but close to the margin

The perimeter counter is mounted over the pin and swung until one of the circles is centered over the intersection in question (Fig. 9). Regardless of where the center of the opposite counter circle lies, the num-

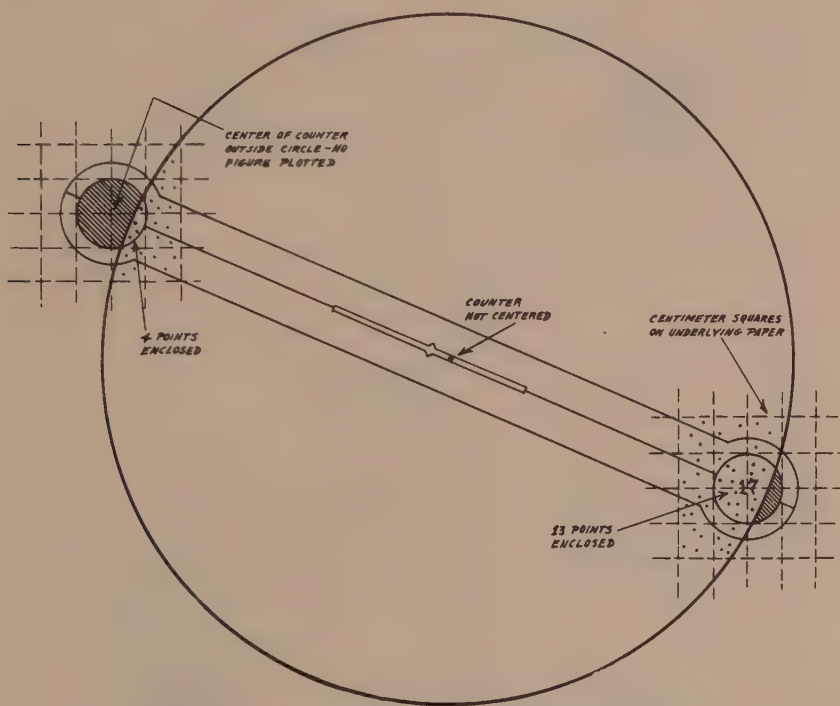


FIG. 9. Diagram illustrating the method of counting when some part of the area within the counter lies outside the circumference although the intersection lies inside.

ber of points in *both* template circles is determined. The points in each circle are then added together, and the figure representing their sum is set down at the center of the circle first adjusted. When one circle has been centered, the other may be centered over an intersection outside the diagram. No figures need be set down at these exterior intersections as they are not required for contouring.

### Case 2. Plotting figures on the circumference of the diagram

Mark off a series of points 1 cm. apart around the circumference of the diagram for at least 180 degrees. Place the perimeter counter over the pin, center it by means of the notches and keep it centered during the following operations. Rotate the counter until a circle is centered over one of the centimeter marks (Fig. 10). Count the number of points in both circles and add them together. On the circumference, at the centers of the two circles of the counter, plot the total number of grains.

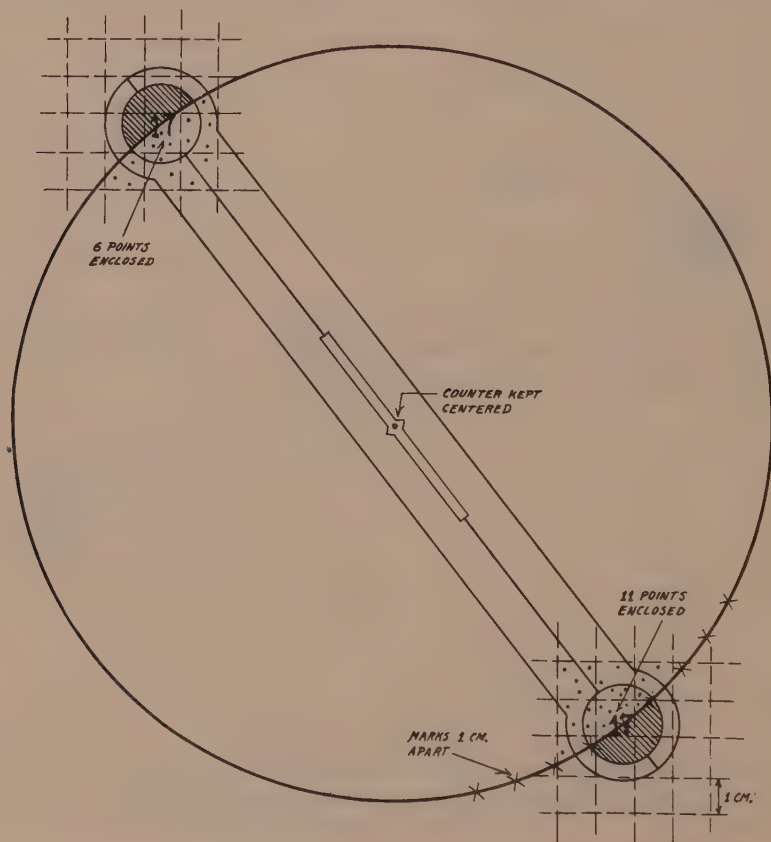


FIG. 10. Diagram illustrating the method of counting along the circumference of the circle.

### Table of percentages

When distribution figures have been plotted at each intersection within the diagram, and at points laid off on the circumference, a table of percentages is drawn up. The number of grains equivalent to 1, 2, 3, 4, etc.,

per cent of the total number measured is calculated. The table is carried out to a percentage equivalent to the largest, or just less than the largest, figure plotted either at an intersection or on the circumference. The figures for the number of grains corresponding to a given percentage of the total are rounded off to the nearest whole number and are then called contour numbers. As an example, we may take a set of figures derived by measurement of 452 quartz axes in a quartz biotite-schist from a section cut normal to the "b" axis. The maximum concentration of poles per unit of area, as indicated by the highest figure determined with the 1 per cent counter was 43. The table is therefore carried out to 9 per cent.

TOTAL NUMBER OF GRAINS MEASURED 452

Per Cent of Grains Measured	Number of Grains	Contour Numbers
0.5	2.26	2
1	4.52	5
2	9.04	9
3	13.56	14
4	18.08	18
5	22.60	23
6	27.12	27
7	31.64	32
8	36.16	36
9	40.68	41

Contours could and may be drawn through all points representing each percentage from 0.5 to 9. But to obtain sufficient detail and clarity, it may not be necessary to draw contours on each per cent. Hence, in the case cited, 2 per cent intervals were used above 5 per cent.

### *Contouring*

Contours are drawn through all points on the diagram with a pole density figure equal to one of the contour numbers. The highest contour is drawn first, i.e., begin by connecting points bearing the largest contour number. Locate the point bearing the highest figure plotted with the counter. Refer to the table and note whether this number is, by chance, equal to the largest contour number. If the two are identical, a contour enclosing this point is drawn. Usually the highest number on the diagram will exceed the largest contour number. For greater accuracy in finding the course of this contour, which defines the maximum, it is advisable to interpolate with the counting template in the area about this highest point.



The number plotted at any intersection point may be the same as a contour number. In such a case the contour passes through the point. Commonly the figure at the intersection is not the same as the contour number. Then the contour passes by the intersection, its proximity depending on the figures adjacent to the intersection in question. The contour is interpolated so as to pass between surrounding intersection points at a distance proportional to the difference between the contour number and the figures at adjacent points. To remove uncertainty as to the course of a contour, the small counting template is centered over intermediate points around the centimeter line intersections (Fig. 11). Figures should first be interpolated at the centers of each centimeter square. Usually in this way the necessary degree of accuracy will be obtained without further interpolation. Any amount of detail desired may be secured by additional interpolation. Particular care should be taken with isolated areas on the diagram, and interpolation carried out until these portions are well demarcated.

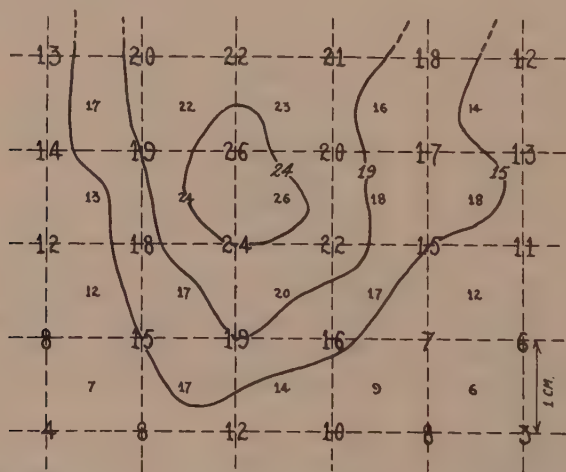


FIG. 11. Sketch illustrating method of drawing contours. Small figures have been interpolated at the center of each centimeter square.

If a contour line intersects the circumference of the diagram, its continuation begins from the point lying diametrically opposite the place of intersection (Fig. 12A). This point is readily found by setting the perimeter counter over the pin and using the center line as a guide.

If a contour number lies exactly on the circumference of the diagram, it is sometimes permissible to draw the contour close to the number rather than to proceed all the way to the margin. Such treatment de-

pend, however, upon the distribution of other contour numbers of the same value and upon the subsequent course of the contour. As seen in Fig. 12B, the No. 7 contour has not been continued to the margin. In the situation indicated it may be drawn so that it approaches the circumference quite closely and then turns away. This prevents small insignificant patches, which disturb continuity, from appearing on the opposite side of the diagram.

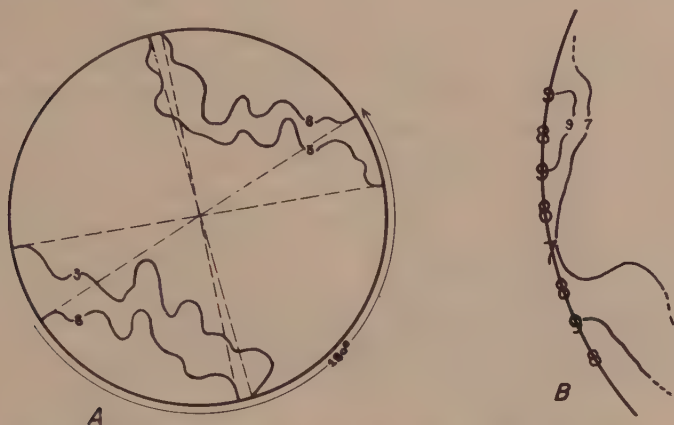


FIG. 12. A. Diagram showing how to locate the continuation of a contour, which has been drawn out to the circumference, by locating the point diametrically opposite the place of intersection.

B. Sketch indicating how the contour line (No. 7 in this instance) may pass close to the circumference to prevent appearance of insignificant patches on opposite side of diagram.

When all contours are drawn, the maxima, which are the areas containing the highest concentration of poles, are marked in solid black. Additional symbols may be applied but in many respects their use is disadvantageous, except, perhaps, if the diagram is being prepared for publication. Even clean-cut symbols, when crowded, or when used in restricted areas, may partially destroy legibility. It is then difficult to rotate the diagram, for such extraneous material on the drawing may cause confusion.

#### ROTATION OF THE DIAGRAM

For purposes of reference and comparison one may rotate the contour diagram so that some other reference axis than that normal to which the section was cut, will stand vertical and emerge at the center of the projection. After rotation the effect and distribution of contours, which would have resulted if a section normal to this other reference axis

had been measured, can be approximated. If a thin section normal to "b" is measured, one may wish to see what pattern would have been derived had a section perpendicular to "a" been examined. By rotation of the contour diagram of the thin section normal to "b" through 90 degrees

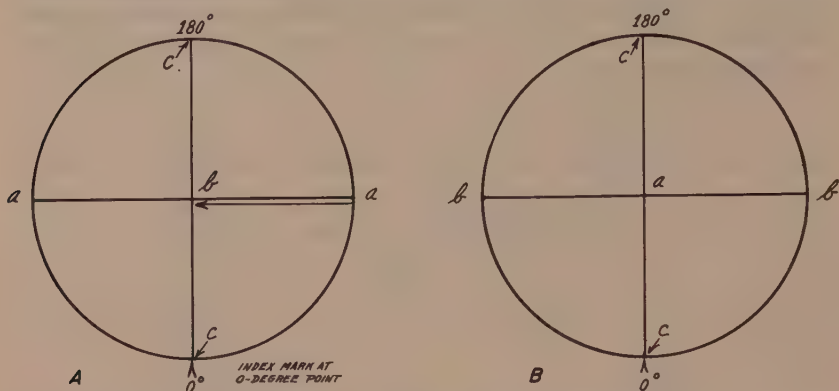


FIG. 13. Rotating the diagram so that the "a" axis is perpendicular. A. The "b" axis is perpendicular to the projection plane, "c" being the axis of rotation.

B. Position of axes after rotation of 90 degrees bringing "a" perpendicular.

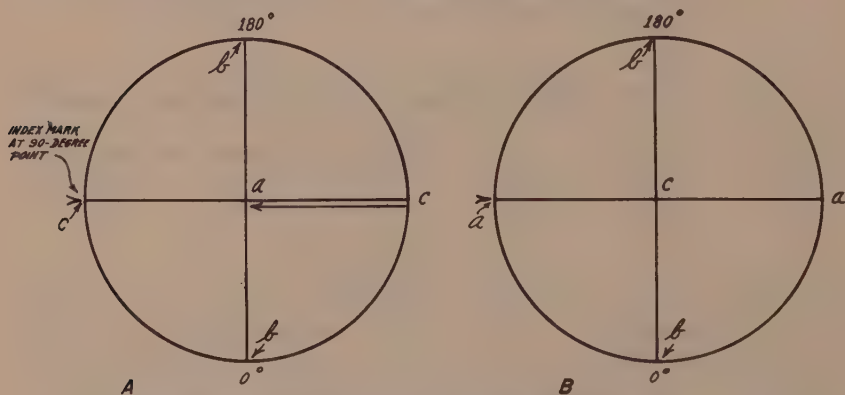


FIG. 14. Rotating the diagram so that the "c" axis is perpendicular. A. The "a" axis stands perpendicular to the projection plane; the "b" axis, in this case, is the axis of rotation.

B. Position of axes after rotation of 90 degrees to bring "c" perpendicular.

about the reference axis "c," the "a" axis can be brought perpendicular to the projection plane. The selection of the correct reference axis for bringing either of the other two reference axes vertical requires clear visualization of the geometric relationships of the measured section with respect to the reference lines established on the hand specimen in the very beginning.



On the equal-area projection rotation can be readily performed because all the great circles projected upon it, with the exception of the 90–270 degree meridian, intersect the equatorial plane of the reference sphere along the same diameter. The trace of this diameter on the projection is the north-south (0–180°) meridian. This 0–180 degree line is, then, at all times the rotation axis of the projection. *The reference axis about which points on the contour diagram are rotated must coincide with this north-south meridian.*

Assembly: Center the contour diagram over the net. Over this center a sheet of tracing paper upon which the customary 20 cm. diameter circle has been drawn. On this upper sheet place an index mark over the index mark on the contour diagram beneath. Fasten the two sheets together so that they may be moved about without shifting relative to one another. Then orient the diagram beneath so that the proper reference axis coincides with the north-south meridian. Fasten the assembly down in this position. The index mark on the original diagram may now coincide with the 0-degree point on the net circumference, or it may lie 90 degrees therefrom. The position of the index mark depends upon which section was measured and which one of the axes it is required to bring vertical, i.e., normal to the projection plane (See Figs. 13 and 14).

Rotation: Select a point on a contour of the original diagram. Along the arc of the vertical small circle lying beneath the selected point count off, in the proper direction, the number of degrees of rotation necessary to bring the required reference axis into coincidence with the vertical axis of the reference sphere, i.e., with the center of the net (Fig. 15A). This process is tantamount to swinging an axis, which passes through the center of the reference sphere, along the surface of the lower hemisphere. During such movement, as long as the axis of rotation coincides with the north-south meridian of the net, the pole will move along the arc of a vertical small circle. If the section measured was cut truly normal to the reference axis, a rotation of 90 degrees is required to bring either of the other two reference axes vertical. If the section was not cut normal to the reference axis, rotation through a varying number of degrees will be required, depending on the individual case. When rotation through the necessary number of degrees is completed place a point on the upper sheet of tracing paper directly over the arc along which the point was carried. Also on the upper sheet, over the original contour, at the point just rotated, place a small cross to avoid repetition. In the same manner rotate additional points on the same contour until a sufficient number have been plotted so that the contour can be accurately delineated in its new position. Connect the points rotated and draw in the contour.

It often happens that before a point has been rotated the necessary



cent, but has never been noted in more than 11 per cent, of all cases.<sup>25</sup> Thin section crystals cut normal, or nearly normal, to the optic axis of a grain of calcite may show twinning lamellae developed in three directions. Ordinarily, however, they are found developed only in one or two directions in the crystal under observation.

Procedure: If the poles of the twinning lamellae in all crystals of calcite in a thin section are to be measured, there is no need for selection. But where lamellae are not present in all cases and measurement of them is definitely selective, those crystals with lamellae can be located easier if the nicols are crossed during preliminary searching. But in any case when the orientation of the twinning plane is actually determined the nicols are uncrossed. In the following procedure it is assumed that the plane of vibration of the polarizer is north-south. As before, the crystal is centered, or at least approximately so, and the horizontal axes of the universal stage are set at zero in the beginning.

1. Rotate the crystal on  $A_1$  until the trace of the lamella is parallel to the east-west crosshair.
2. Rotate on  $A_4$  until the lamella is reduced to the thinnest, sharpest line possible.

When the crystal has been brought into this position the twinning plane stands vertical with respect to the universal stage and is parallel to the microscope axis. Its pole can now be plotted.

Plotting the pole of the normal to the twinning plane: Inscribe a circle 20 cm. in diameter on a piece of tracing paper; center this circle over the Schmidt net; and fasten the sheet in place over the pin. Place the index mark on the circumference.

1. Rotate the tracing paper until the index mark lies over the figure on the net circumference corresponding to the  $A_1$  reading.
2. On the north-south (0-180 degree) meridian of the net plot the pole from the reading obtained on  $A_4$ .

When the drum of  $A_4$  is rotated toward the observer, so that the reading was, let us say, 330 degrees, count toward the center from the 180 degree point on the net circumference, and find the figure corresponding to the  $A_4$  reading. Plot the pole at this point on the north-south meridian (Fig. 16). If the drum of  $A_4$  is turned away from the observer, the pole is located by counting along the north-south meridian from the south (0-degree) point toward the center of the net.

While at Innsbruck the writer was instructed to measure these lamellae by bringing the trace parallel to the east-west crosshair in the manner just described. The morphological relationship between the fundamental rhombohedron " $r$ " ( $10\bar{1}1$ ) and the rhombohedron " $e$ " is

<sup>25</sup> Sander, B., *opus cit.*, p. 202.



such that when working with the lamellae in the east-west position the difference in index of refraction between the "e" ray of calcite (1.486) and that of the segments (1.64 approx.) should be taken into consideration. For highest accuracy in plotting, the special scale used when plotting the pole of the optic axis of calcite after the crystal is brought into the equatorial position, should also be employed if such accuracy is de-

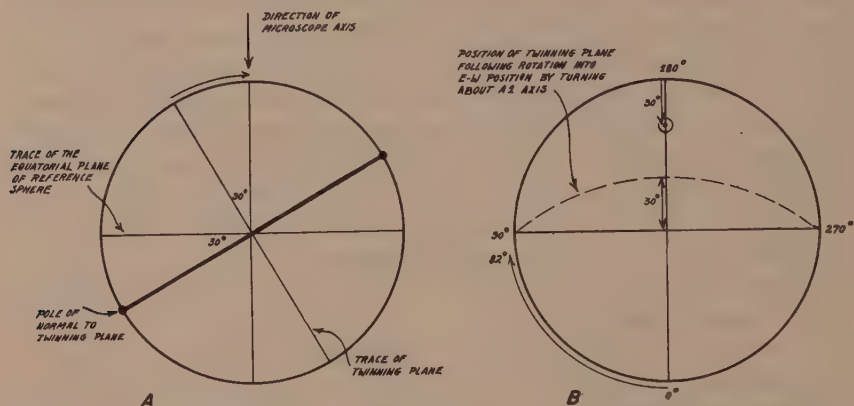


FIG. 16. Plotting poles of calcite lamellae; coordinate  $A_1$   $82^\circ$ ,  $A_4$   $30^\circ$ . A. Relationship of the normal to the twinning plane and the reference sphere.

B. Tracing paper rotated until the index lies at  $82^\circ$  point. Pole plotted on N-S meridian  $30^\circ$  in from the circumference.

manded. In such a case the corrections for the different angles of inclination on  $A_4$  should be laid off on the north-south meridian. Ordinarily such precautions are not required for routine measurements. An alternative method is to rotate the trace of the lamella parallel to the north-south crosshair. But if this practice is followed the relief of a grain will be relatively less, and as a rule the position of rotation at which the trace forms the finest possible line cannot be detected so easily.

In general, whenever the optic axes of calcite are measured, the lamellae which are present should be measured at the same time. One plots the pole of the optic axis first and assigns a number to this pole. The poles of the lamellae in the crystal are then numbered correspondingly. For example, if the pole were number 6, then  $6'$ ,  $6''$ ,  $6'''$  could represent the respective lamellae measured.

### *Measurement of mica*

Muscovite and biotite are measured in the same manner as calcite lamellae by rotation on  $A_1$  until the trace of the basal cleavage lies parallel to the east-west crosshair. Then by rotation on  $A_4$  the cleavage trace is reduced to the finest possible hairline. The stage should be ro-

tated on  $A_4$  both toward and away from the observer. It will then be seen that the trace of the cleavage plane widens notably on both sides of the vertical position and the correct fine adjustment can be determined more accurately. The poles of the normals to the cleavage planes are plotted in the same manner as the poles of calcite lamellae.

Sometimes the orientation of the mica flakes and the plane of the thin section are such that basal sections are obtained. If we are measuring a biotite which is not too dark in color so that extinctions can be observed, the pole of the optic axis can be determined by the same methods used for measurement of the uniaxial minerals. Biotite can be treated in this way because, for practical purposes, the acute bisectrix  $X$  may be considered to stand perpendicular to (001).

#### DIAGRAMS SHOWING THE ORIENTATION OF ELONGATE, PRISMATIC AND ACICULAR MINERALS

One may wish to determine the orientation of elongate crystals which lie approximately in a well-marked structural plane. The minerals best suited to treatment by the method given here are those which are frequently prismatic or acicular in habit, as hornblende, apatite or tourmaline. For these diagrams the optical orientation of a grain is not specifically measured, for only the azimuths of the elongate crystals are determined. A "*garbenschiefer*" containing abundant hornblende needles is an example of a rock amenable to investigation of this nature. The method can, however, be used for elongated crystals of quartz, calcite, and sections of mica cut nearly normal to the basal plane. In general, the procedure is adapted to all types of minerals where in-equidimensional form and idiomorphic tendency are pronounced.

Assembly: A circle 20 cm. in diameter is drawn on a sheet of tracing paper and an index mark placed on the circumference. The tracing paper is superposed and centered on the Schmidt net, and the index mark brought to the 0-degree point on the circumference.

Procedure: Each crystal of the selected mineral is brought to the intersection of the crosshairs by moving the thin section along the guiding edge of the sledge. By turning about the  $A_1$  axis (horizontal axes set at zero), the crystal is rotated until the cleavage trace (as with hornblende or mica) or the long axis (as with apatite prisms or tourmaline needles) is parallel to one of the crosshairs.

For a given set of measurements either crosshair can be used as a reference line, but no change should ever be made during the measurements. It will be assumed here that the north-south crosshair is used. Only one-half of the projection is required for plotting and when measuring from the north-south crosshair only the lower semicircle on the tracing paper is utilized. By a series of traverses every grain of the

selected mineral encountered is measured and its azimuth plotted until a sufficient number for statistical purposes have been secured.

**Plotting:** Rotate the tracing paper until the index mark lies at the point on the net circumference corresponding to the reading of the  $A_1$  circle. *Over the 0-degree mark on the net*, using a very fine pen, place a short line on the inside of the circumference (Fig. 17A). To avoid con-

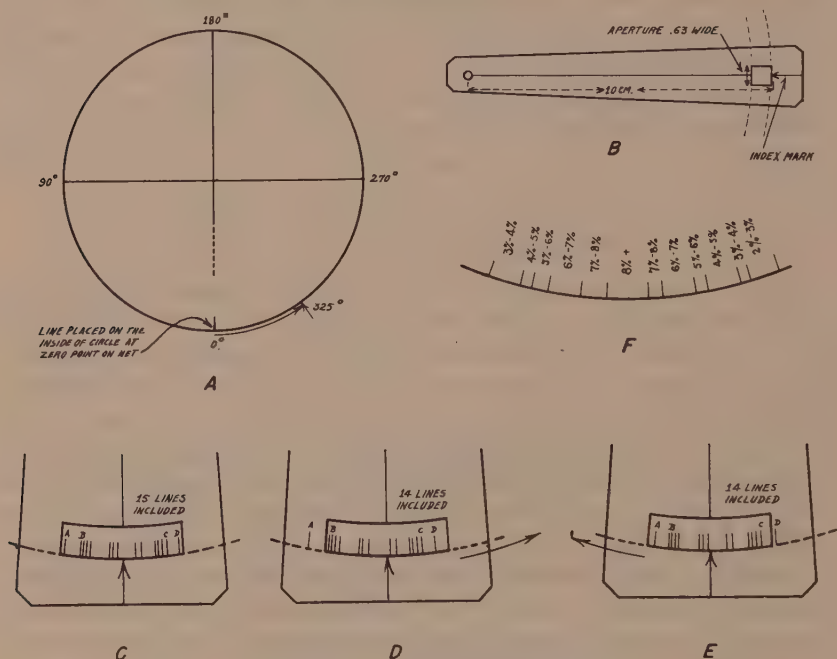


FIG. 17. A. Diagram illustrating the method of plotting azimuths.

B. One per cent template used for counting percentages of grains with various azimuths.

C, D, E. Sketches showing successive steps in determining the length of arc containing a given percentage of lines.

F. Appearance of diagram after arcs have been determined with counting template.

fusion bring the index mark of the tracing paper back to the 0-degree mark on the net after plotting the line. Sometimes the crystals will have such conspicuous orientation that many of these short lines will overlap. One can then place a figure above the line indicating the number of grains with this same azimuth.

### *Making the diagram*

When a sufficient number of grains are plotted the percentage of grains having various azimuths can be graphically represented. A seg-



ment of a circle equal in length to  $1/100$ th of the circumference of the net is usually taken as a reference unit. Since the diameter of the net is 20 cm. a segment representing  $1/100$ th of the circumference will be 0.63 cm. long. For measuring the segment intercepts a template is used. A strip of celluloid approximately 2 cm. wide and 12 cm. long is obtained and a line scribed down the middle. On this line, about 1 cm. from one end make a small puncture. Ten centimeters from this point an arc is drawn across the strip. Approximately 1 cm. above this arc another is lightly scribed. From the point where the lower arc crosses the median line of the strip a distance of 0.315 cm. is laid off on both sides of the point. Celluloid is then cut away from between the two arcs leaving an aperture which exposes a segment equal to 1 per cent of the net circumference (Fig. 17B).

Assembly: The tracing paper on which the grain azimuths have been plotted is fastened to a drawing board, and over this another sheet of transparent paper with the usual circle 20 cm. in diameter is placed. The two sheets are firmly fastened together. An index mark is placed on the upper sheet exactly over the index on the diagram beneath. The celluloid template is fastened at the center of the circle with a pin. The template should now swing freely and the bottom of the aperture should be flush with the circumference of the circle.

Table of Percentages: A table of percentages indicating the number of grains representing different amounts of the total measured is drawn up. This table is carried out until the maximum number of grains included in the aperture at the point of greatest concentration of lines is just exceeded. Let us assume that the azimuths of 174 grains have been measured and that the largest number of grains included within the 1 per cent template is found to be 15. Nine per cent of the total grains measured exceeds by one the largest number included in the aperture (see table).

Per Cent of Grains Measured	Number of Grains	Segment Numbers
1	1.74	2 grains
2	3.48	3 grains
3	5.22	5 grains
4	6.96	7 grains
5	8.70	9 grains
6	10.44	10 grains
7	12.18	12 grains
8	13.92	14 grains
9	15.66	16 grains

Counting: The template is first swung to the point on the circumference showing the greatest concentration of lines. In the example cited the template is swung until 15 grains, equal to 8+ per cent of the total, are included (Fig. 17C). The length of the arc containing 8 or more per cent of the total number of lines must now be found. The template is moved, right or left, from the area of maximum concentration, until the aperture includes just 14 grains (Fig. 17D). When exactly the number of lines specified by this lower limit are included, a mark is set on the circumference of the circle *at the point where the index of the aperture lies*. The template is then swung in the opposite direction until 14 lines are again included in the aperture and another mark placed at the aperture index (Fig. 17E).

The segment defined by these two lines is a portion of the circle having 14 or more lines and 8+ per cent of all grains measured lie with their long axes within the azimuth range indicated. Counting is continued by swinging the template until the aperture includes the number of lines indicated by the segment number of the next lower percentage. In our case this figure is 12, representing a number of grains equivalent to 7 per cent of the whole. Counting and dividing off of the circumference continues in this manner until each percentage is considered.

The lines made on the circumference should be at least 5 mm. long and the areas between adjacent lines should be numbered with the corresponding percentages represented (Fig. 17F). When counting is completed symbols may be used to designate different percentages and the variation in frequency and orientation. If the lines are very much congested it may be advisable to use a set of percentages including a larger number of grains per unit. Units of from 0-2 per cent, 2-4 per cent, 4-6 per cent may then be found more satisfactory. If relatively few grains are measured the plotted lines may be too sparse for working conveniently with the 1 per cent aperture. In such case templates with apertures of 1.26 cm (2%) or 1.89 cm. (3%) or even larger may be employed.

#### ACKNOWLEDGMENT

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# JOHANNSENITE, A NEW MANGANESE PYROXENE\*

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## INTRODUCTION

At the December, 1932, meeting of the Mineralogical Society of America, at Cambridge, Mass., the writer presented a short paper on a new manganese pyroxene. Since then the same mineral has been found to occur at several additional localities, and abundant material from one of these localities, namely, Puebla, Mexico, having been obtained, a more complete study of the mineral has been made. As the publication of the full report may be delayed for some time, it seems desirable to present, as an extended abstract, the data upon which the new mineral is established.

Johannsenite, named in honor of Professor Albert Johannsen of the University of Chicago, is the manganese analogue of the monoclinic pyroxenes diopside and hedenbergite, with the formula  $\text{MnO} \cdot \text{CaO} \cdot 2\text{SiO}_2$ , containing theoretically 28.68 per cent of MnO. X-ray powder photographs show that it has the same structure as diopside and hedenbergite.

## OCCURRENCE

The new mineral has been determined to occur at the following localities: Bohemia mining district, Lane County, Oregon; at the Empire Zinc Company's mine near Hanover, New Mexico; Franklin, New Jersey; near Schio, Venetia, Italy; Campiglia, Tuscany, Italy; Tetela de Ocampo, Puebla, Mexico; Pachuca, Hidalgo, Mexico; and probably at Rezbanaya, Hungary; Elba; and Algeria.

Johannsenite forms columnar, radiating, and spherulitic aggregates of fibers and prisms, generally of a clove-brown, grayish, or greenish color, and in appearance resembles some grayish diopside and light colored hedenbergite. The presence of black stains of oxide of manganese however is indicative of the presence of manganese. The columnar and radiating prisms from Venetia, Italy, are several inches long and the greenish spherulites from Puebla, Mexico, are an inch and a half thick (Fig. 1). The brown spherulites and masses of radiating prisms of johannsenite from Oregon rarely exceed a quarter of an inch in size. The minute brown crystals from Franklin, New Jersey, are embedded in bustamite.

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At all of the occurrences except Franklin, New Jersey, some of the johannsenite is in places changed to rhodonite and at Puebla, Mexico, the released calcium silicate has been redeposited as xonotlite (the white area in Fig. 1).

The change from johannsenite to rhodonite has taken place in one of three ways. (1) The rhodonite forms irregularly shaped masses em-



FIG. 1. Greenish spherulites of johannsenite from Tetela de Ocampo, Puebla, Mexico. The white area is xonotlite with dendrites of oxide of manganese. Natural size.

bedded in the johannsenite. Under crossed nicols the rhodonite shows a moiré effect due to wavy extinction bands. The prismatic structure of the original johannsenite has completely disappeared. All stages of the change, from a little rhodonite to abundant rhodonite with only a little residual johannsenite, can be seen in thin sections. This type of alteration is very abundant in the material from Puebla, Mexico, and to a lesser extent in that from Oregon, New Mexico, and Venetia, Italy.

(2) A pseudomorphic change; the prisms of johannsenite retain

their shape and yield compact columnar rhodonite with, however, the continuity of the long prisms of original johannsenite broken.

(3) Development of euhedral crystals of rhodonite at the ends of the prisms of altered johannsenite.

In one specimen from Puebla, Mexico, the development of massive pink rhodonite embedded in the brownish and grayish johannsenite and as a pink border along the ends of the johannsenite prisms is very well shown. Some specimens from both Oregon and New Mexico have altered to impure black oxide of manganese, and in one thin section of the material from Mexico, long prisms of johannsenite have been replaced by calcite. Like many silicates of manganese, johannsenite is prone to incipient alteration, and oxidation, hydration, and carbonatization products are common.

In Oregon, johannsenite occurs in a quartz vein in rhyolite and at Puebla, Mexico, it is reported to be in a calcite vein in rhyolite. At the other localities it is a product of contact metamorphism of a limestone. Quartz, calcite, and rhodonite are the most abundant associated minerals. Characteristic metallic associates are magnetite, pyrite, sphalerite, galena, and chalcopryite.

#### PROPERTIES

The cleavage is good parallel to the prism  $m\{110\}$ . Other planes of separation, as observed under the microscope, are parallel to  $c\{001\}$ ,  $a\{100\}$ , and  $b\{010\}$ . The density of pure johannsenite, free from magnesium and iron, has been calculated as about 3.6, but owing to partial alteration and the presence of impurities (chiefly calcite and quartz), massive pieces of the mineral yield lower values, ranging from 3.2 to 3.5. The powdered material from Puebla, Mexico, (analysis no. 2) has a density of 3.53.

The optical axial plane is parallel to  $b\{010\}$ , and extinction is  $48^\circ \pm$ ; optically positive,  $2V$  about  $70^\circ$ , dispersion  $r > v$ . Polysynthetic twinning lamellae are common. The indices of refraction for pure  $\text{MnO} \cdot \text{CaO} \cdot 2\text{SiO}_2$  are:  $\alpha = 1.710$ ,  $\beta = 1.719$ ,  $\gamma = 1.738$ , calculated from the measured values on material whose composition is known, and correcting for the presence of isomorphous diopside and hedenbergite.

The measured indices of refraction, together with the component composition as deduced from the chemical analyses, are shown in Table 1. On account of the compensating effect of magnesium and iron, the measured indices of several of the samples are nearly the same as those of the magnesium- and iron-free pure  $\text{MnO} \cdot \text{CaO} \cdot 2\text{SiO}_2$ .

TABLE 1. MEASURED INDICES OF REFRACTION OF JOHANNSENITES WITH THEIR COMPONENT COMPOSITION

	Locality	Measured			Component composition J = $\text{MnO} \cdot \text{CaO} \cdot 2\text{SiO}_2$ D = $\text{MgO} \cdot \text{CaO} \cdot 2\text{SiO}_2$ H = $\text{FeO} \cdot \text{CaO} \cdot 2\text{SiO}_2$ Z = $\text{ZnO} \cdot \text{CaO} \cdot 2\text{SiO}_2$			
		$\alpha$	$\beta$	$\gamma$	J	D	H	Z
1	Venetia, Italy	1.710	1.719	1.738	97	1	2	0
2	Puebla, Mexico	1.709	1.718	1.737	95	3	2	0
3	Puebla, Mexico	1.710	1.719	1.738	95	2	3	0
3a	Tuscany, Italy	1.709	1.717	1.735	86	9	5	0
4	Hanover, New Mexico	1.713	1.721	1.740	81	3	16	0
5	Oregon	1.709	1.718	1.736	76	12	12	0
6	Venetia, Italy	1.708	1.718	1.737	72	14	14	0
7	New Jersey	1.697	1.706	1.725	51	32	9	8

## REFERENCES

1. Roebing collection, U. S. Nat. Mus., Cat. no. R3118. Analysis no. 1.
2. From specimen illustrated in Fig. 1. U. S. Nat. Mus., Cat. no. 97484. Analysis no. 2.
3. From a different specimen containing considerable rhodonite. Analysis no. 3.
- 3a. Material from Harvard University. Component composition approximate, based on an old analysis.
4. Collected by A. C. Spencer. Analysis no. 4.
5. Collected by J. T. Pardee. Analysis no. 5.
6. Collected by D. F. Hewett. Analysis no. 6.
7. Furnished by L. H. Bauer. Minute brown crystals embedded in bustamite. Crystals hand picked by Miss J. J. Glass. Analysis no. 7.

Johannsenite fuses readily (about 4) before the blowpipe flame to a non-magnetic glassy bead whose color depends on the quantity of iron present. The purest mineral (nos. 1 and 2) fuses to an amber colored translucent bead; if several per cent of iron is present (nos. 4, 5 and 6) the bead is darker brown and more opaque. Hedenbergite fuses to a black, opaque, magnetic bead. All the samples analyzed yield a little water when heated in a closed tube and show a slight effervescence when treated with HCl, due to the presence of impurities and slight alteration. The powdered mineral is completely decomposed by evaporation with HCl, if nearly pure  $\text{MnO} \cdot \text{CaO} \cdot 2\text{SiO}_2$ .



## ANALYSES

All the samples analyzed, except that from Franklin, New Jersey, contained some rhodonite. Pure johannsenite should contain 22.69 per cent of CaO and as no rhodonite contains more than about 11 per cent of CaO, the presence of admixed rhodonite in the samples analyzed will lower the percentage of CaO. In addition to rhodonite, small quantities of quartz, calcite, sphalerite, and undetermined oxidation, hydration, and carbonatization products were present.

Seven analyses of johannsenite have been made. They are listed in Table 2 in the order of decreasing content of pure  $\text{MnO} \cdot \text{CaO} \cdot 2\text{SiO}_2$ . These analyses have been recalculated (Table 3) deducting impurities other than quartz and rhodonite, except for analysis no. 3 in which about 18 per cent of rhodonite was deducted. The  $\text{CO}_2$  was deducted as calcite except for analysis no. 5 in which the  $\text{CO}_2$  was equally distributed between Ca and Mn. The  $\text{H}_2\text{O}$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{Fe}_2\text{O}_3$ , and ZnS were deducted as such.

The slightly high ratios of  $\text{SiO}_2$  in Table 4 are ascribed to admixed quartz and the slightly low ratios of CaO to admixed rhodonite.

TABLE 2. ANALYSES OF JOHANNSENITE

No.	1	2	3	4	5	6	7
Locality	Venetia, Italy	Puebla, Mexico	Puebla, Mexico	New Mexico	Oregon	Venetia, Italy	New Jersey
Analyst	Schaller	Steiger	Schaller	Schaller	Schaller Richardson	Schaller	Fairchild
$\text{SiO}_2$	48.16	47.62	50.24	48.15	42.84	47.62	50.30
MnO	27.82	27.47	29.94	21.37	23.61	21.15	14.85
MgO	0.23	0.53	0.26	0.48	2.06	2.74	6.19
FeO	0.50	0.70	0.88	4.28	3.20	4.31	2.59
ZnO	—	—	—	—	—	—	3.27
CaO	20.56	22.18	18.16	20.88	20.99	20.15	22.97
$\text{Al}_2\text{O}_3$	—	0.91	0.32	0.31	—	0.81	—
$\text{Fe}_2\text{O}_3$	—	0.04	0.25	1.58	0.59	0.62	—
$\text{CO}_2$	1.02	0.24	—	1.39	3.86	2.07	—
$\text{H}_2\text{O}-$	0.55	0.09	0.15	0.24	0.58	0.19	—
$\text{H}_2\text{O}+$	0.58	0.40	0.49	0.96	1.57	0.25	—
ZnS	0.34	—	—	0.17	0.77	0.25	—
$\text{MnO}_2$	0.11	—	—	—	—	—	—
	99.87	100.18	100.69	99.81	100.07	100.16	100.17

TABLE 3. RECALCULATED ANALYSES OF JOHANNSENITE

	1	2	3	4	5	6	7
SiO <sub>2</sub>	50.18	48.29	51.27	51.56	49.17	51.02	50.58
MnO	28.99	28.09	26.83	22.89	23.52	22.66	15.28
MgO	0.24	0.54	0.32	0.51	2.37	2.94	6.37
FeO	0.52	0.72	1.07	4.59	3.67	4.62	2.67
ZnO	—	—	—	—	—	—	2.56
CaO	20.07	22.36	20.51	20.45	21.27	18.76	22.54
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

TABLE 4. RATIOS OF RECALCULATED ANALYSES OF JOHANNSENITE

	1	2	3	4	5	6	7
SiO <sub>2</sub>	2.07	1.98	2.11	2.11	2.00	2.07	2.00
(Mn, Mg, Fe, Zn)O	1.04	1.03	0.99	0.99	1.08	1.11	1.05
CaO	0.89	0.98	0.90	0.90	0.92	0.82	0.95

TABLE 5. MINERALOGICAL IDENTITY OF "HIGH LIME RHODONITES" LISTED IN STANDARD REFERENCE BOOKS

No.	Dana	Hintze	Doelter	Locality	Per cent CaO	Mineral
1	—	VII	1	Italy	13.23	Mixture of rhodonite and johannsenite
2	11	XXVII	—	Mexico	16.45	Mixture of rhodonite and johannsenite
3	—	XXVI	5	Mexico	14.57	Mixture of rhodonite and johannsenite
4	10	XXVIII	—	Mexico	9.60	May have been all rhodonite but probably contained some johannsenite
5	—	VIII	3	Italy	18.72	Mixture of johannsenite and rhodonite
6	13	IV	—	Hungary	21.02	Johannsenite and a little rhodonite
7	—	XXII	—	New Jersey	18.00	Bustamite
8	12	X	2	Sweden	18.16	Bustamite

The standard reference books contain six analyses of johannsenite, or probably more accurately of mixtures of johannsenite and rhodonite, as the low percentages of CaO indicate that considerable rhodonite must have been present in the material analyzed. These six analyses are listed in the standard text books under rhodonite, generally as bustamite. They include analyses of material from (1) Monte Civilla, Vicentia, Italy (Pisani, 1886); (2, 3, and 4) three analyses, Puebla, Mexico (Ebelmen, 1845; Dumas, 1826; and Rammelsberg, 1866); (5) Campiglia, Tuscany, Italy (von Rath, 1868); and (6) Rez-

banya, Hungary (Sipöcz, 1873). The references and mineralogical interpretations of these six analyses are shown below in Table 5 together with two other analyses (7 and 8) of "high-lime rhodonites," which are bustamites.

#### RELATION TO OTHER ANHYDROUS SILICATES OF MANGANESE

Isomorphous mixtures of johannsenite and hedenbergite, known as manganhedenbergites, are not rare. Small quantities of the diopside constituent are usually present. Schefferite is dominantly diopside with Mn, Fe, and Zn substituting for part of the Mg, and CaO-free components of the  $\text{RO} \cdot \text{SiO}_2$  type are present to a small extent. In jeffersonite, no component of the  $\text{RO} \cdot \text{CaO} \cdot 2\text{SiO}_2$  ( $\text{R} = \text{Mn, Mg, Fe, Zn}$ ) type is dominant.

The bustamites have a different structure. They are of the wollastonite type, and are a homogeneous solid solution of  $\text{CaO} \cdot \text{SiO}_2$  (wollastonite) with  $\text{MnO} \cdot \text{SiO}_2$ . Optical data have been obtained for examples with percentages of MnO ranging from a few per cent, through 6, 7, 25, 28 per cent to a maximum of 33 per cent of MnO, or 61 per cent of  $\text{MnO} \cdot \text{SiO}_2$ . Those bustamites in which the ratio of MnO to CaO is close to 1:1, represent a dimorphous form of  $\text{MnO} \cdot \text{CaO} \cdot 2\text{SiO}_2$ , whose optical properties are very different from those of johannsenite as shown in Table 6.

TABLE 6. OPTICAL PROPERTIES OF THE DIMORPHOUS FORMS OF  $\text{MnO} \cdot \text{CaO} \cdot 2\text{SiO}_2$

	Johannsenite $\text{MnO} \cdot \text{CaO} \cdot 2\text{SiO}_2$	Bustamite (Mn, Ca) $\text{O} \cdot \text{SiO}_2$ $\text{MnO}:\text{CaO}=1:1$
System	Monoclinic	Triclinic
$\alpha$	1.710	1.671
$\beta$	1.719	1.685
$\gamma$	1.738	1.687
B	0.028	0.016
Sign	Positive	Negative
Ext.	$48^\circ \pm$	$<15^\circ$
2V	$70^\circ$	$40-44^\circ$

Bustamite with a 1:1 ratio of MnO and CaO, is the high-temperature modification, johannsenite the low-temperature form, with the transition temperature about  $830^\circ\text{C}$ . Johannsenite, on ignition, inverts to bustamite.

The name bustamite was given in 1826 by Brongniart to the material from Puebla, Mexico, now known to be a mixture of johannsenite and rhodonite. Since 1922, however, the term bustamite has been applied to



a different and distinct mineral whose optical properties were first determined by Larsen and Shannon<sup>1</sup> and their reallocation of the name bustamite has been followed by all subsequent writers on these minerals.

Rhodonite is different from both johannsenite and bustamite. A compilation of all analyses of authenticated rhodonites shows that the maximum content of CaO is about 11 per cent, which may be represented by the formula  $3\text{MnO} \cdot \text{CaO} \cdot 4\text{SiO}_2$ . The content of CaO in rhodonites ranges down to a minimum of 1.31 per cent. Any so-called rhodonite with a greater percentage of CaO than about 11 per cent is probably not rhodonite but some other mineral, probably either johannsenite or bustamite. All rhodonites are optically positive with a large axial angle. Synthetic products which have been referred to rhodonite in the past should more correctly be referred to pyroxmangite, which is a triclinic mineral of the same general type of formula, namely,  $\text{RO} \cdot \text{SiO}_2$ , with R essentially Mn and Fe.

Plotting the variation of indices of refraction with percentages of CaO for these minerals on one diagram shows that johannsenite, bustamite, rhodonite, and pyroxmangite are distinct minerals and do not form a continuous series between any two or more of them, even though they are very similar in composition.

Rhodonite: Essentially  $\text{MnO} \cdot \text{SiO}_2$  with  $\text{FeO} \cdot \text{SiO}_2$  and  $\text{CaO} \cdot \text{SiO}_2$  and minor quantities of  $\text{MgO} \cdot \text{SiO}_2$  and  $\text{ZnO} \cdot \text{SiO}_2$ .

Bustamite: Essentially  $\text{MnO} \cdot \text{SiO}_2$  with  $\text{CaO} \cdot \text{SiO}_2$  and minor quantities of  $\text{FeO} \cdot \text{SiO}_2$ ,  $\text{MgO} \cdot \text{SiO}_2$ , and  $\text{ZnO} \cdot \text{SiO}_2$ .

Pyroxmangite: Essentially  $\text{MnO} \cdot \text{SiO}_2$  with  $\text{FeO} \cdot \text{SiO}_2$  and minor quantities of  $\text{CaO} \cdot \text{SiO}_2$  and  $\text{MgO} \cdot \text{SiO}_2$ .

Johannsenite: Essentially  $\text{MnO} \cdot \text{CaO} \cdot 2\text{SiO}_2$  with minor quantities of  $\text{MgO} \cdot \text{CaO} \cdot 2\text{SiO}_2$  and  $\text{FeO} \cdot \text{CaO} \cdot 2\text{SiO}_2$ .

<sup>1</sup> Larsen, E. S., and Shannon, E. V., Bustamite from Franklin Furnace, New Jersey: *Am. Mineral.*, vol. 7, pp. 95-100, 1922.

## PREHNITE FROM COOPERSBURG, PENNSYLVANIA

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WITH MORPHOLOGIC DESCRIPTION by

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### ABSTRACT

Well-developed prehnite has been found in the Triassic diabase near Coopersburg, Pennsylvania. The crystals are tabular parallel to the base and show the forms  $c\{001\}$ ,  $a\{100\}$ ,  $m\{110\}$ ,  $s\{111\}$ ,  $o\{011\}$ ,  $b\{010\}$ ,  $p\{221\}$ , and  $t\{012\}$ . The forms,  $p$  and  $t$ , are new. Chemical and spectroscopic analyses are presented and the optical properties described.

### OCCURRENCE

A new occurrence of prehnite crystals has been found near Coopersburg, Berks County, Pennsylvania. This material merits description because of the excellent development of the prehnite crystals which present two new forms.

The prehnite occurred in a vein-like body cutting Triassic diabase where it was exposed in a quarry. The vein material occupied a steeply-dipping irregular fissure extending 30 or 40 feet across the quarry face. The width of the fissure ranged from a fraction of an inch to about 8 inches. In the wider places the filling was not complete and prehnite crystals had opportunity for free growth. Some of the vein filling, which was virtually all prehnite, was massive but none of it showed the characteristic irregular botryoidal structure typically exhibited by the prehnite found at Paterson, and other New Jersey localities.

Adjacent to the walls and throughout the narrower parts of the vein the prehnite shows the more usual development of crystals radiating from a common center. This manner of growth results in interpenetrating spherical masses of radiating crystals. Where the fissure was wider and the crystals had an opportunity for free growth, terminated tabular crystals project into the open space. These crystals form fan-like aggregates as shown in Fig. 1. Comparing this structure to a wheel, the  $a$ -axes form the spokes, the  $b$ -axes are parallel to the axle, and the  $c$ -axes are tangent to the rim. The crystals show the usual basal cleavage as well as an imperfect breaking parallel to the front pinacoid which is probably a parting (Fig. 2). The average size of the terminated crystals is  $2 \times 12 \times 0.4$  mm. The color of the prehnite is a delicate light green, somewhat lighter than that from Paterson.

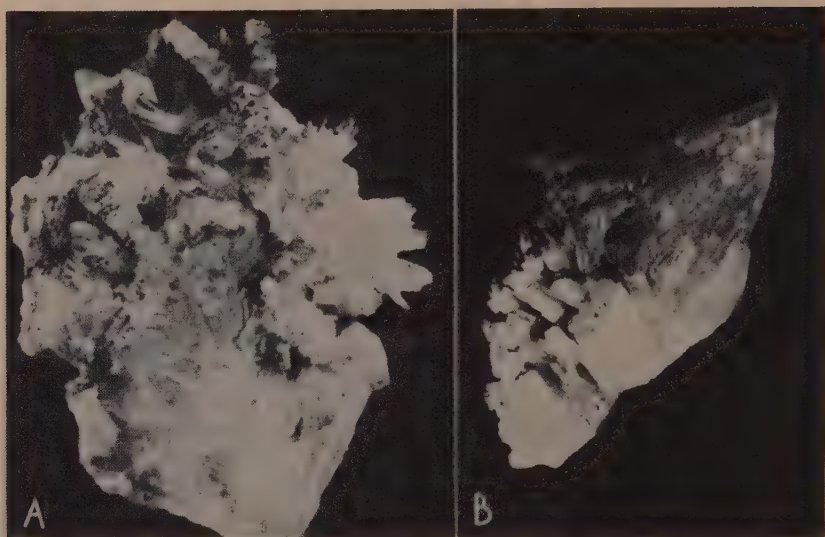


FIG. 1A. Group of prehnite crystals showing radial development and terminated individual.  $\times 2\frac{1}{2}$

FIG. 1B. Prehnite group showing characteristic development.  $\times 2$



FIG. 2. Individual prehnite crystals showing typical microscopic aspect. Note parasitic crystal growths parallel to the basal pinacoid and lighter bands bordering prism trace caused by birefringence variation of the pyramid. Crossed Nicols,  $\times 20$ .



Quartz prisms are scattered throughout the prehnite near the walls of the vein. They formed subsequent to the earlier development of prehnite. Iron and manganese stains occur to a small extent throughout the material.

The normal diabase near Coopersburg is composed of labradorite, augite, magnetite and sphene. Adjacent to the prehnite vein this mineral assemblage has been altered to a massive greenish-gray rock composed of uralite, quartz, and epidote with a little residuary sphene. It is interesting to note the complete absence of labradorite in the altered rock.

### ANALYSES

Comparative spectroscopic analyses of prehnite from Coopersburg and from Paterson, New Jersey, are listed in Table 1.

It is very probable that the elements present in minor amounts are due in greater part, at least, to minute physically-contained impurities.

TABLE 1. SPECTROSCOPIC ANALYSES OF PREHNITE FROM COOPERSBURG, PA., AND PATERSON, N. J.

Element	Coopersburg	Paterson
Si	principal	principal
Ca	principal	principal
Al	principal	principal
Fe	appreciable (-)	appreciable (+)
Mg	small	small
Mn	trace	minute trace
Cu	very minute trace	very minute trace

A chemical analysis<sup>1</sup> of the Coopersburg prehnite is listed in Table 2, which is in excellent agreement with the accepted composition.

TABLE 2. AVERAGE OF TWO ANALYSES

SiO <sub>2</sub>	42.38
Al <sub>2</sub> O <sub>3</sub>	24.41
CaO	27.90
H <sub>2</sub> O	4.10
Fe <sub>2</sub> O <sub>3</sub>	1.20
	99.99

<sup>1</sup> J. R. Wiegner, *Analyst*.

## OPTICAL DESCRIPTION

The optic plane is parallel to (010);  $X=a$ .  $(+ )2V=64^\circ$  measured. Tabular, elongation negative.  $\alpha=1.612\pm.002$ ,  $\beta=1.618\pm.002$ ,  $\gamma=1.642\pm.002$ . Birefringence, 0.030. Colorless in section.

According to Winchell (1933),<sup>2</sup> optic anomalies in prehnite are not uncommon. The optic angle is subject to marked variation, interference colors and dispersion may be abnormal, and incomplete extinction may occur. Microscopic striations and twinning lamellae have been noted, and it is believed that where these are submicroscopic, anomalous properties result.

In the Coopersburg prehnite, the measured optic angle,  $(+ )2V=64^\circ$ , is about  $10^\circ$  greater than the optic angle calculated from the indices of refraction. The abnormal azure-blue and leather-brown interference colors described by Iddings (1906) are present in some sections. Sections perpendicular to the optic axes exhibit incomplete extinction.

Individual crystals show striations on the basal plane which are parallel to the prism and front pinacoid. These lack the extinction properties typical of twinning striations and are thought to be due to oscillatory growth. Some crystals (Fig. 2) by their birefringence show the presence of tiny pyramid faces. Small parasitic crystals have grown parallel to the basal plane on many of the larger crystals. Many of the parasitic crystals exhibit only pinacoid forms (Fig. 2).

Thin sections of the massive material located closer to the vein walls show abundant twinning. The two types most commonly encountered are: (1) Two sets of fine twinning lamellae parallel to the traces of the prism faces intergrown to form a grid, and (2) two sets of fine twinning lamellae parallel to the traces of the front and side pinacoids. The latter type is somewhat coarser and commonly shows discontinuous bands that resemble a blocky type of microcline twinning.

Previous workers explain the anomalous optical properties of prehnite by assuming submicroscopic twinning. Study of the Coopersburg prehnite has not served to prove or disprove this assumption.

## MORPHOLOGIC DESCRIPTION

From a casual inspection of the prehnite one would think that there was abundant material for crystal measurements. However, a close examination shows that the pyramid faces on most of the crystals do not give suitable reflections. Out of 25 of the most promising crystals examined, only 6 were suitable for goniometric measurement. All of the crystals are similar in habit, being tabular parallel to the base as shown in Fig. 3.

<sup>2</sup> References are listed at the end of the article.

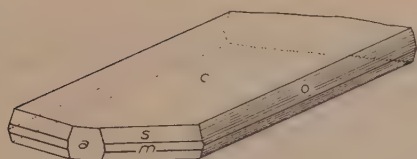
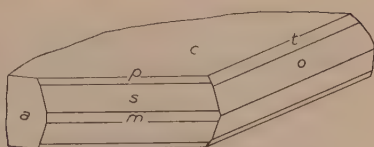


FIG. 3. Characteristic development of prehnite.

FIG. 4. Portion of prehnite crystal showing the two new forms,  $p$  and  $t$ .

The forms common to all the crystals are  $c\{001\}$ ,  $a\{100\}$ ,  $m\{110\}$ ,  $s\{111\}$ , and  $o\{011\}$ . The brachypinacoid  $b\{010\}$  was found on only two crystals, but the tendency for  $b$  to form, gives  $o$  a striated appearance. On most of the crystals  $s$  is deeply etched, and on only 6 crystals were the faces of this form of sufficient quality to give reflections for measurement. The other common forms, however, presented brilliant faces on most crystals.

Two new forms were noted as line faces as shown in Fig. 4;  $p\{221\}$  on two crystals and  $t\{012\}$  on one crystal. The position of these forms is given by the following two-circle goniometer measurements.

Forms	Mean		Range		No. of Faces
	$\phi$	$\rho$	$\phi$	$\rho$	
$p$ 211	49°59'	69°07'	49°55'–50°01'	68°55'–69°19'	3
$t$ 012	0°00'	59°44'	—	59°27'–60°01'	2

At least six different axial ratios have been given for prehnite by as many writers. Goldschmidt (1890) gave the ratio as  $a:b:c=0.840:1:3.376$ , but later (1897) he recorded  $a:b:c=0.8405:1:1.1207$ . Dana (1892) gave  $a:b:c=0.840:1:0.5626$ . These last two ratios have persisted to the present day. Gossner and Mussgnug (1931) in an  $x$ -ray study of prehnite found the dimensions of the unit cell to be:  $a_0=4.65$ ,  $b_0=5.52$ ,  $c_0=18.53$ , giving a ratio of  $a_0:b_0:c_0=0.842:1:3.357$ . Using this ratio, which agrees closely with Goldschmidt's original, the Miller indices of the forms on the crystals at hand are considerably simplified, and this latter ratio has therefore been used in assigning indices to the forms found.

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2. Goldschmidt, V. (1890): Krystallformen der Mineralien, Berlin.
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# ANDALUSITE IN PEGMATITE FROM FRESNO COUNTY, CALIFORNIA

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## INTRODUCTION

Although far from unknown, the occurrence of andalusite in pegmatites is rather unusual. Such an occurrence has been found, however, on the western slope of the Sierra Nevada, in Fresno County, California. The locality was discovered by Dr. Cordell Durrell, and has been studied by the senior author in connection with regional geologic mapping of the surrounding territory. It lies in the west-central part of the Academy Quadrangle, about 17 miles northeast of the city of Fresno, and 8 miles S60°E of the town of Friant, in the south-central part of Section 20, T11S, R22E, Mount Diablo Base and Meridian.

The writers wish to express their appreciation to Dr. Adolf Pabst of the University of California for his aid and advice during the course of the studies.

## GENERAL GEOLOGY

The pegmatitic dike in which the andalusite is found is narrow and poorly exposed. Most of the material collected was in the form of float on the hillside below the outcrop. The dike cuts across a series of meso-zone schists, consisting largely of plagioclase amphibolites derived by dynamothermal metamorphism from basaltic to andesitic volcanic rocks, with smaller amounts of quartz-mica schist and calc-silicate rocks of meta-sedimentary origin. The two latter types are rare in the immediate vicinity of the dike. The metamorphic terrain is extensively intruded by large bodies of quartz diorite, which form a part of the batholithic complex of the Sierra Nevada.

## PARAGENESIS

The pegmatite is composed almost entirely of quartz and oligoclase ( $Ab_{88}$ ), with a few flakes of muscovite and a little clinocllore. The last-named mineral has a small 2V, averaging about 15°, and a negative sign;  $\beta = 1.596$ ,  $\gamma - \alpha = .009$ . The rock is moderately coarse grained, the individual grains averaging about 4 mm. across. The texture is hypidior-morphic to pegmatitic. Throughout most of the rock feldspar is about twice as abundant as quartz, but locally feldspar is nearly or completely absent, and the rock has the aspect of a hypothermal quartz vein.

Andalusite is found scattered irregularly through the pegmatite, in prismatic and radiating masses. In color, it varies from pale pink to dark

reddish-violet. The masses range in size from less than 1 cm. to as much as 10 cm. across, and from about 1 cm. to nearly 15 cm. in length. Each mass is partly or completely surrounded by a greenish-gray rim, up to a centimeter in thickness, which is composed of very fine-grained, dense sericite. The outer surface of the sericite envelope is in many instances coated with large flakes of muscovite, and in some specimens muscovite can be seen lying along the cleavage faces within the andalusite.

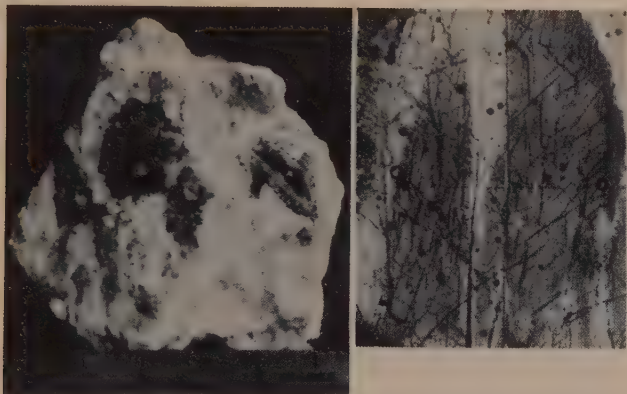


FIG. 1. Andalusite (A) in pegmatite, surrounded by rims of fine grained sericite (S).

FIG. 2. Thin section of andalusite showing alternation of light and dark material. Ordinary light,  $\times 7\frac{1}{2}$ .

Under the microscope, the andalusite is seen to carry many small included grains of corundum, scattered with random orientation through the host crystal. They are pleochroic from pale blue parallel to the *c* crystallographic axis to colorless. Each grain of corundum is surrounded by a narrow rim of fine-grained muscovite. In some slides narrow zones of muscovite lie parallel to the prismatic cleavage of the andalusite. Some of the smaller masses of andalusite are made up of a single crystal, but all of the larger masses, and many of the smaller ones are composed of an aggregate of crystals, in nearly parallel arrangement. Rims of sericite irregularly embay the edges of the andalusite, giving the appearance of having replaced it, and in a few places narrow veinlets of the sericite cut irregularly across the andalusite.

#### COLOR VARIATIONS IN THE ANDALUSITE

Of the greatest interest, however, are the color variations within the andalusite. The color differences mentioned as being apparent in the hand specimen are even more striking under the microscope. In the dark

material the X direction is a deep pink in color, while in the light material it is nearly colorless. Y and Z are colorless to very pale oil green in both varieties. All gradations are found from one extreme of color to the other. In most places the light and dark varieties are interdigitated parallel to the *c* axis in a more or less regular manner, but in other places irregular spots of dark material are enclosed within the light. Boundaries between the two varieties are in most places quite sharp. There is present also a zoning parallel to the base, in which bands of lighter material cross the dark grains. In this case the passage from one zone to the next is in most instances gradational.

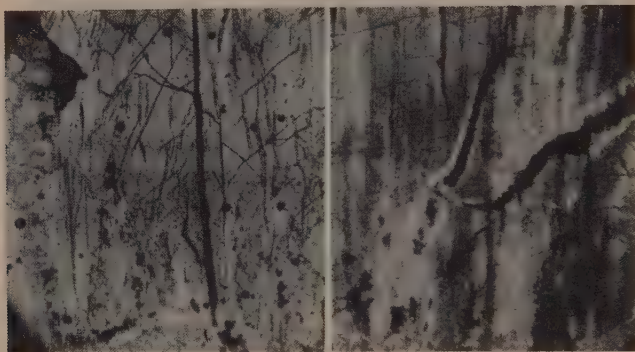


FIG. 3. Thin section of andalusite showing color zoning parallel to the base. The rim of fine grained sericite can be seen embaying the andalusite on the left. Ordinary light,  $\times 7\frac{1}{2}$ .

FIG. 4. Thin section of andalusite, showing alternation of light and dark material parallel to the prismatic cleavage. The andalusite is cut by two veinlets of sericite. Ordinary light,  $\times 7\frac{1}{2}$ .

In addition to the difference in pleochroic colors, the light and dark varieties of andalusite show slight differences in the indices of refraction and birefringence, and a notable difference in the size of the optic axial angle. The dark variety shows very strong rhombic dispersion, while in the light type dispersion is extremely weak. The indices of refraction were determined by the immersion method, and are subject to a possible error of  $\pm .002$ . The values for  $2V$  were determined with a universal stage both by direct observation and by the extinction angle method of Berek.<sup>1</sup> They are accurate to about  $\pm 2^\circ$ . Specific gravity determinations were made using thallium formate solution and a Westphal balance. The values obtained for the specific gravities show notable differences between the lightest and the darkest material, although, as is the case with the other properties, there exist all gradations from the lightest to the

<sup>1</sup> *Neues Jahrb. Mineralogie, Beil. Band 48*, pp. 34-62, 1923.



darkest varieties. The properties determined for the two extreme varieties are as follows:

<i>Lightest andalusite</i>	<i>Darkest andalusite</i>
$\alpha = 1.634$	$\alpha = 1.637$
$\beta = 1.639$	$\beta = 1.641$
$\gamma = 1.645$	$\gamma = 1.646$
$\gamma - \alpha = 0.011$	$\gamma - \alpha = 0.009$
$(-)\gamma = 86^\circ$	$(-)\gamma = 75^\circ$
$r < v$ , weak	$r < v$ , very strong
$G. = 3.13$	$G. = 3.16$

In order to determine the cause of the differences in properties, both the light and dark material have been analyzed chemically and spectrographically. The spectrographic examinations were made by Dr. T. G. Kennard of Claremont, California, and yield the following results:

	<i>Lightest andalusite</i>	<i>Darkest andalusite</i>
Large amount	Al	Al
	Si	Si
Small (X.%)	Fe	Fe
Very small (0.X%)	Na	—
Traces		
(0.0X or 0.00X%)	Li	Li
	K	Na
	Ca	Ca
	Mg	Mg
	Cr	Cu
	Cu	Ga
	Ga	Ge
	Ge	

The only element present in sufficient quantity and likely to produce the observed differences in properties is iron. Accordingly, the two extreme types of material have been analyzed quantitatively for silica, alumina, and iron. The results are given below.

	<i>Lightest andalusite</i>	<i>Darkest andalusite</i>
SiO <sub>2</sub>	35.61%	35.46%
Al <sub>2</sub> O <sub>3</sub>	62.40	60.84
Fe <sub>2</sub> O <sub>3</sub>	0.51	2.44
FeO	0.60	0.42
H <sub>2</sub> O+	0.41	0.24
H <sub>2</sub> O—	0.32	0.26
Total	99.85	99.66

R. H. Merriam, *analyst*.

There is thus a notable difference in the ferric iron content of the two

varieties of andalusite. Moreover, the difference in percentage of  $\text{Fe}_2\text{O}_3$  is nearly equal to the difference in percentage of  $\text{Al}_2\text{O}_3$ , suggesting that the ferric iron replaces alumina in the mineral. It is well known that  $\text{Fe}_2\text{O}_3$  produces dispersion,<sup>2</sup> and the efficacy of small amounts of ferric iron as a coloring agent is generally recognized. It seems, therefore, an entirely justifiable conclusion that the differences in properties between the light and dark varieties of andalusite are caused by the variation in ferric iron content.

Many analyses of andalusite containing ferric iron are recorded in the literature,<sup>3</sup> and Niggli suggests that the iron substitutes for aluminum.<sup>4</sup> The suggestion seems entirely possible, since the two elements do not differ greatly in atomic radii. There has been, however, little or no attempt made to correlate iron content with optical properties, although Simpson suggests that the deep purple color of certain andalusites from Western Australia is caused by the presence of iron and titanium.<sup>5</sup>

Zoned andalusite, in which an inner kernel of deep violet color is surrounded by a pale pink outer border, has been described by several writers from Scaletta Pass in the canton of Graubünden, in Switzerland.<sup>6</sup> The color of this material was ascribed by Gramman to the presence of  $\text{TiO}_2$  in the dark variety. Spaenhauer called attention, however, that Gramman's conclusion is not established, since he did not directly demonstrate the presence of titanium. At a still earlier date, Weinschenk argued for titanium sesquioxide as the coloring matter of many minerals,<sup>7</sup> but the suggestion appears to have little to support it in connection with the Scaletta material. However, titanium in any form can not be the cause of the physical and optical differences in the andalusites described in the present paper, since not even a trace of titanium was revealed by the spectrographic analyses.

#### ORIGIN

Andalusite in igneous rocks is usually regarded as of xenolithic origin, resulting from the metamorphic action of the magma on inclusions of

<sup>2</sup> Larsen, E. S., and Berman, H., Microscopic Determination of the Nonopaque Minerals, *U. S. Geol. Survey, Bull.* **848**, p. 32, 1934.

<sup>3</sup> Doelter, C., *Handbuch der Mineralchemie*, Bd. 2, Abt. 2, pp. 4-9, 1917.

<sup>4</sup> Niggli, P., *Lehrbuch der Mineralogie*, Bd. 2, pp. 255-256, 1926.

<sup>5</sup> Simpson, E. S., Contributions to the mineralogy of Western Australia—Series VI, *Jour. Roy. Soc. W. Australia*, vol. 17, pp. 137-148, 1931.

<sup>6</sup> Gramman, A., Ueber die Andalusitvorkommnisse im rhätischen Flüela- und Scalettagbiet und die Färbung der alpinen Andalusite, *Viertelj. Schrift d. Naturf. Ges. Zürich*, vol. 44, pp. 302-352, 1899; abst., *Zeits. Krist.*, Bd. 35, pp. 407-410, 1901.

Spaenhauer, F., Die Andalusit- und Disthenvorkommen der Silvretta; *Schweiz. min. und pet. Mitt.*, Bd. 13, pp. 323-345, 1933.

<sup>7</sup> Weinschenk, E., *Zeits. der deutsch. geol. Gesellschaft*, Bd. 48, pp. 704-712, 1896; abst., *Neues Jahrb. f. Min.*, II, pp. 372-373, 1898.

aluminous wall-rocks. On the other hand, large bodies of andalusite have recently been ascribed to the concentration of alumina from surrounding rocks under the influence of high temperatures and abundant emanations from nearby intrusive bodies.<sup>8</sup> In the present case, however, it seems improbable that either of these suggestions will account for the origin of the andalusite. The dike is only a few inches in width, and cuts sharply across the enclosing rocks, making it unlikely that the andalusite masses represent altered xenolithic material. No traces of relict metamorphic structures or textures are present. The surrounding schists are not highly aluminous, and show no evidences of alteration or leaching, so that it appears highly unlikely that there could have been a migration of alumina to the dike from the adjacent wall-rocks. Moreover, if the andalusite had developed by reaction with xenoliths torn from the adjacent rocks, the process must necessarily have involved the almost complete removal of the abundant iron and magnesia present in the latter, since the andalusite and the surrounding pegmatite are almost devoid of these substances. The vein is so narrow that it seems very unlikely that xenoliths of rock types different from those at the present surface could have been carried up from greater depths, and even if this were possible, highly aluminous rocks are totally unknown throughout the entire district. The only alternative left is to consider the andalusite as of magmatic origin, the alumina having been introduced by solutions given off from the magma reservoir at depth.

The andalusite formed later than the quartz and feldspar of the enclosing pegmatite. This period of formation of corundum and andalusite must have been marked by the introduction of solutions, gaseous or liquid, carrying a great excess of alumina. Alkalies must have been nearly absent, since otherwise they would have combined with the alumina and silica to yield feldspar. Moreover, during the period of formation of the corundum, even silica must have been present in insufficient quantity to combine with the alumina to produce andalusite.

At a somewhat later time the concentration of alkalies in the solutions increased to a point at which the previously formed andalusite was no longer stable, and reaction occurred between the andalusite and the alkali-bearing hydrous solutions producing a rim of sericite surrounding the andalusite core. Similar sericitic rims are present in the material from Scaletta Pass described by Spaenhauer,<sup>9</sup> and are likewise ascribed

<sup>8</sup> Kerr, P. F., The occurrence of andalusite and related minerals at White Mountain, Calif.: *Econ. Geol.*, vol. 27, pp. 614-643, 1932.

Kerr, P. F., and Jenney, P., The dumortierite-andalusite mineralization at Oreana, Nev.: *Econ. Geol.*, vol. 30, pp. 287-300, 1935.

<sup>9</sup> *Op. cit.*, pp. 330-334.



by him to an alteration of the andalusite, involving essentially an addition of alkalis and water.

Andalusite is characteristically a high-temperature mineral, and by analogy with the more complete paragenetic associations described from other localities,<sup>10</sup> both the andalusite and the corundum are probably to be regarded as of pneumatolytic origin. The sericite represents a later, hydrothermal stage, of lower temperature. The latter is in accordance with Rogers<sup>11</sup> conclusions as to the hydrothermal origin of sericite.

The probable conditions from the foregoing considerations include solutions, hydrous at least in the later stages, which underwent a gradual change in composition. Highly aluminous at the time of formation of the corundum, they became progressively richer, first in silica, and then in alkalis. This theory of gradually changing conditions is similar to that generally invoked to account for the order of deposition of the metallic minerals in ore deposits, and likewise to that set forth by a number of recent writers to account for the formation of many complex pegmatites.<sup>12</sup>

#### CONCLUSION

The andalusite was developed by pneumatolytic action following the crystallization of the surrounding pegmatite. The aluminous vapors were of magmatic origin. At a later time, hydrothermal solutions attacked the andalusite and altered it in part to sericite. The optical and physical differences between the light and dark varieties of andalusite are due to the larger amount of ferric iron in the latter.

<sup>10</sup> Kerr, P. F., *op. cit.*

Kerr, P. F., and Jenney, P., *op. cit.*

<sup>11</sup> Rogers, A. F., Sericite a low temperature hydrothermal mineral: *Econ. Geol.*, vol. 11, 118-150, 1916.

<sup>12</sup> Schaller, W. T., The genesis of lithium pegmatites: *Am. Jour. Sci.* (5), vol. 10, pp. 269-279, 1925.

Landes, K. K., The paragenesis of the granite pegmatites of central Maine: *Am. Mineral.*, vol. 10, pp. 355-411, 1925.

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# DIRECT PROJECTION OF OPTIC FIGURES

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## TABLE OF CONTENTS

Summary.....	595
Introduction.....	595
Use of uranium glass block.....	596
Luminosity of light rays.....	596
Use of polaroid plate.....	596
Uranium glass and polaroid plate in conjunction.....	596
Calibration of the uranium glass block.....	596
Box type 2E goniometer.....	598
A new microscope method.....	599
A celluloid protractor 2E goniometer.....	600
Projection upon a hemisphere.....	603
A new direct projection stage.....	604

## SUMMARY

Uranium glass causes transmitted light beams to appear luminous when viewed in a darkened room. A block of uranium glass permits the cone of light transmitted above a microscope stage from a substage converging lens to be viewed as a three-dimensional feature. An optic figure may be transmitted through such a glass block and be viewed upon a ground glass surface of the block. Making allowances for the index of refraction of the glass, and its thickness, a scale was drawn upon the surface from which the optic angle,  $2E$ , of biaxial minerals has been read directly. By suitable apparatus here described the optic angle in air ( $2E$ ) has been measured megascopically in terms of its tangent by one device and measured directly upon a semi-circular goniometer and upon a hemisphere. All these devices depend upon the use of a polaroid plate as an analyzer. Similar measurements have been made under the microscope by the use of a glass plate with ground glass surfaces on one-half of each side, using a micrometer ocular, Bertrand lens, and analyzing nicol. The writer describes a new detachable accessory stage which permits direct projection of optic figures upon a translucent hemisphere and direct reading of the azimuth and elevation of emergent optic axes.

## INTRODUCTION

The writer has developed certain simplified methods for the demonstration of optic figures and for the measurement of optic angles, which may be found useful by other teachers. Suitable mineral sections of course are a requisite. Many of the devices here to be described may be made out of the materials usually available, even in unpretentious

laboratories. It is the purpose of this paper to describe and explain the methods and the equipment used.

#### USE OF URANIUM GLASS BLOCK

##### *Luminosity of light rays*

A block of uranium glass may be used on the stage of a petrographic microscope to illustrate the form of a convergent light beam. A transmitted beam of light within uranium glass is luminous in a darkened room. The luminosity of the beam permits an observer to see where the convergent beam comes to a point within the glass block. By lowering and raising the sub-stage fixture the position of the focus of the convergent beam may be adjusted to coincide with the base of the glass block. From the side the beam appears conical in shape and from above clearly circular.

##### *Use of polaroid plate*

If one places a suitable section of a uniaxial mineral above the converging lens, and covers that with a piece of polaroid, an optic figure may be formed on a piece of ground glass or tracing paper held above the polaroid plate. Due to the fact that the beam of light is divergent upwards, the figure increases in size, and of course decreases in brightness, with increase in distance between the mineral section and the ground glass screen.

##### *Uranium glass and polaroid plate in conjunction*

One may combine the uranium glass block and the polaroid sheet, and project an optic figure upon one side of the block (previously prepared by fine grinding), while the luminous beams are clearly visible through the transparent sides of the block. The axial cross shows from the side as two black stripes, at positions 90 degrees apart, cutting through the luminous body of the projection. By this means the optic figure is revealed in three dimensions. Even more interesting are the demonstrations possible with biaxial minerals. In these cases phenomena depending upon rotation of the principal optic plane, including display of the optic angle, may be observed very conveniently.<sup>1</sup>

##### *Calibration of the uranium glass block*

For any mineral the optic angle,  $2H$ , observed through the uranium glass is dependent both on the true angle,  $2V$ , of the mineral and on the index of refraction of the glass, as well as upon the intermediate index

<sup>1</sup> This apparatus was demonstrated at the meetings of the Illinois State Acad. Science, Quincy, Illinois, April 27, 1936. *Trans. Illinois State Acad. Science*, vol. 29, p. 177, 1936.



of the mineral concerned. Fortunately the glass block, supplied to the writer by the Bausch and Lomb Optical Company, is just one centimeter thick and a little more than 2 centimeters square. Careful measurement shows that the glass block has an index of refraction slightly greater than 1.50. The distance between isogyres of a biaxial mineral projected upon the ground glass surface of the block, is equal to twice the tangent of the angle  $H$  multiplied by the thickness of the block, which is unity, one centimeter. By Snell's Law,  $n \sin H$  equals  $\sin E$ ; in this case  $n$  equals 1.5. A simple relation can be computed between the distance on the surface of the uranium glass block, the angle  $H$  in the glass, and the angle  $E$ , which is the corresponding angle for transmission through air. The writer constructed a graph from computation, and then scaled off distances from the center of the block to read directly the angle  $2E$  as shown by the emergence of the optic eyes from a suitable mineral section. Thus, the optic axes of biaxial minerals may be projected through the block of uranium glass, and the angle  $2E$  for each mineral section may then be read from the scale. The reading is only approximately correct, because the great magnification makes the isogyres wide relative to the scale divisions marked upon the ground glass surface. The writer found it convenient to draw the scale upon the ground glass surface with India ink.

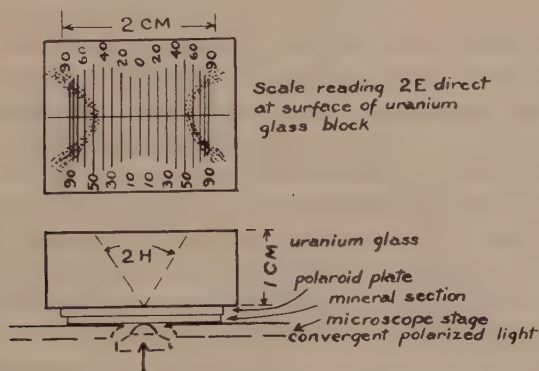


FIG. 1. Diagram to indicate the use of a block of uranium glass calibrated so as to show the value of  $2E$  by direct projection with strong sub-stage illumination. Natural size.

The divisions are marked on the block as follows:

Distance	Angle $E$
1.2 mm.	10 degrees
2.4	20
3.6	30
4.8	40

6.0	50
7.2	60
8.2	70
8.7	80
9.0	90

For each mineral the value  $2V$  must be computed from the value read for  $2E$ , according to the value of the intermediate index of refraction of the mineral concerned.

In actual operation it was found that the thickness of the polaroid plate may become an obstacle to correct focussing of the converging lens upon the base of the uranium block. In that case the writer merely transferred the polaroid plate from the base to the surface of the uranium block, and read the position of the isogyres thus made visible upon the scale through the polaroid.

The values of  $2E$  and  $2V$  so obtained are correct within the limits of the small scale on which the angle  $2E$  is read. However, the measurements are very quickly made, and the processes involved are simple to understand. In principle they are the same as those used in the well known Mallard's method for measurements made under the microscope.

#### BOX TYPE $2E$ GONIOMETER

The disadvantages of making a special scale on the uranium glass block is avoided by another device in which the angles are read in air. This has the further advantage that the location of convergence of the optic angle is of no particular importance. The writer placed in a paste-board box two celluloid scales marked in millimeters and centimeters in parallel position, one centimeter apart in a vertical direction, the edge of each parallel to a vertical plane, but lying on opposite sides of the plane. The top of the box has an open slot through which all the top scale and the central part of the lower scale may be read. There is a hole also in the bottom of the box. The lower scale is about  $\frac{1}{2}$  cm. above the base of the box, but this distance is not material. This box may be placed over a polaroid plate on a suitable mineral section, the edges of the scales may be adjusted into the projection of the principal optic plane of the mineral. Each scale then shows one-half of the optic figure, the vertical plane between the scales passing through both optic eyes, and the isogyres appearing at the same time on both scales. The distance between the isogyres is read as closely as possible on each scale. The difference in the distances as read in both scales divided by two, is equal to the tangent of the optic angle in air ( $E$ ). This is true no matter how thick the polaroid plate and how far away from the mineral section the two scales may be. So long as the scales are separated by a constant

distance, they read at every distance from the mineral section the same angular inclination of the projected rays.

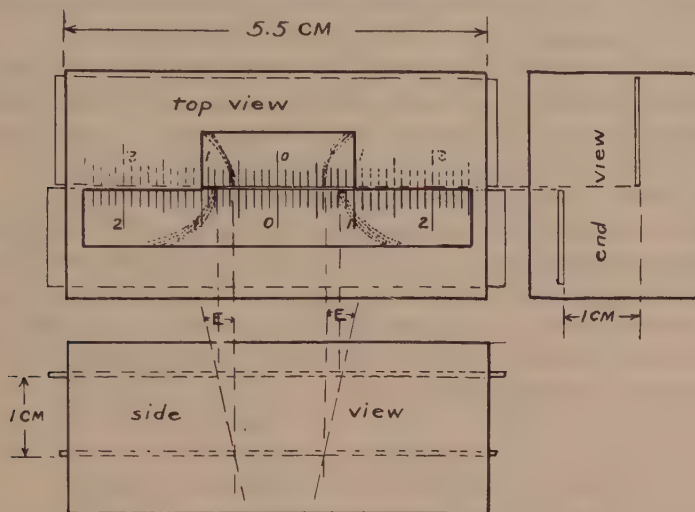


FIG. 2. Box type of 2E goniometer, having two scales one cm. apart, indicating the position of the isogyres of an optic figure on both scales simultaneously. Actual size.

This apparatus is easily and cheaply made, and it is more accurate in operation than the uranium glass block. It requires no calibration, because its measurements are of absolute value, not dependent upon any variables incident to its own construction or composition. It reads accurately up to values of about 140 degrees for 2E without being made more than 5 cm. long. Higher angles require a longer upper scale, which becomes unwieldy and very difficult to read with any confidence due to the spreading in width of the isogyre due to magnification, and to the faintness of projection due to the increased distance from the mineral grain to the point of emergence of the isogyre on the scale.

#### A NEW MICROSCOPE METHOD

From the foregoing megascopic devices may be derived a microscope method of considerable accuracy. This method may be applied to the examination of mineral grains in a thin rock section, and does not require the use of a polaroid plate. The writer measured the index of refraction of an ordinary microscope glass slide. Then he covered one half of each side of the slide with "Scotch cellulose tape," up to a medial line, in such a way that each clear side was faced with a covered side. Then he treated each clear side with a "ground glass" liquid. As soon as the ground glass

surface developed and dried satisfactorily, the writer stripped off the cellulose tissue leaving the glass in those places bare and clean. Thus was produced a glass plate with ground glass surface covering one-half of each side. By placing this plate over a mineral section so that the plane of division between the two ground glass surfaces lies in the principal optic plane of the mineral, one provides a set-up comparable to that of the megascopic "box type" goniometer above described. Using a micrometer eyepiece with no objective, but retaining the Bertrand lens and crossed nicols, one may observe the optic figure on both the top and bottom of the glass plate, and the observer may measure the distances between the isogyres on both sides of the plate. One-half the difference in these distances divided by the thickness of the plate (measured in the same units) is equal to the tangent of the optic angle in the glass plate. Sine E equals the sine of the angle, H, in glass multiplied by  $n_x$ , the index of refraction of the glass plate.

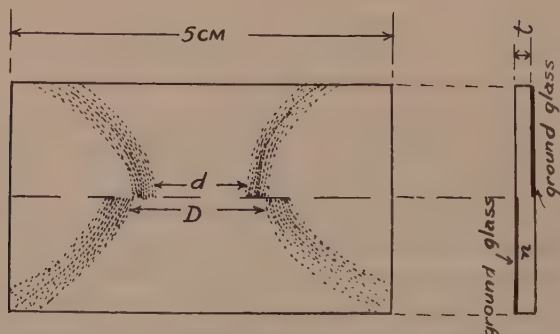


FIG. 3. Glass plate 2E goniometer for use under microscope. One-half of each side is ground glass. Diagram shows appearance of the optic figure projected onto each side of the plate simultaneously. Natural size.

$$\frac{1}{2}(D-d) = \tan H \times t$$

$$\sin E = n_x \sin H$$

$D$  = distance between the isogyres on the top of the glass

$d$  = distance between the isogyres on the bottom of the glass

$H$  = optic angle in the glass of the slide

$t$  = thickness of the slide in micrometer units

$n_x$  = index of refraction of the glass slide.

#### A CELLULOID PROTRACTOR 2E GONIOMETER

Arising from the projection of biaxial optic figures upon tracing paper over an analyzing plate of polaroid came the use of a semicylindrical scale on which the angle 2E may be read directly.



This device<sup>2</sup> is made of two semicircular protractors, preferably of celluloid, 5 cm. in radius, which are attached to a base 10 cm. long and 2 cm. wide, and with a hole 1 cm. in diameter in the middle. The semicircles are joined by a semitranslucent strip 2 cm. in width, which is a protractor numbered from zero at the zenith to 90 degrees at each horizon. This is placed over a biaxial section which gives a good optic figure preferably in a position such that the acute bisectrix passes through the zenith. When the section is turned to the 45 degree position with the isogyres passing through the eye, the angle E can be read in both directions from zero. In case the acute bisectrix is really vertical these two angles will be the same, otherwise they may be added together, if they are not too eccentric, and their sum may be taken as being closely equivalent to 2E.

The principal sources of error of this instrument arise from the fact that the angle 2E as measured on this goniometer may not be exactly concentric with the curvature of the scale. It is assumed that the rays of light which pass through the center of the optic eye are exactly parallel to the radii of the goniometer, but in certain cases they may not be quite parallel because the point of convergence of the condensing lens may be either slightly above or slightly below the base line of the semicircular goniometer. That error is minimized by having the device made with a radius of 5 cm., which is so large in proportion to the probable lack of coincidence between the point of condensation of the lens and the center of the protractor's circle that any difference is practically negligible. In any case it seems impossible that this difference could amount to more than 1/10 of a cm. in a vertical direction, which, with a radius of 5 cm. and small angles, would be entirely insignificant and only in the case of readings where 2E is more than 40 degrees could the error amount to more than 1 degree.

Another model is made with a radius of  $2\frac{1}{2}$  cm. This has the advantages of much greater brilliance of the projected figures, and use on the stage of the microscope without withdrawing the barrel, but it has the disadvantage that the error discussed above becomes much more serious, especially for minerals with high values for 2E.

This goniometer may be made out of sheet celluloid cut with slots and tabs to fit together. Once put together the parts may be fastened with an acetone-base cement, after which the projecting ends of the tabs may be cut off with scissors. The scale is drawn on tracing paper and cemented onto the celluloid strip after the main parts are put together. The polaroid analyzing plate must be accurately cemented in place on the base

<sup>2</sup> Trans. Ill. State Acad. Science: vol. 29, pp. 177-178, 1936. *Am. Mineral.*, vol. 22, p. 217, 1937.

piece of the goniometer before it is assembled. Care must be taken to be sure that the polarizing direction of the polaroid is such that it is crossed with reference to the substage polarizer when the goniometer is placed in the 45 degree position.

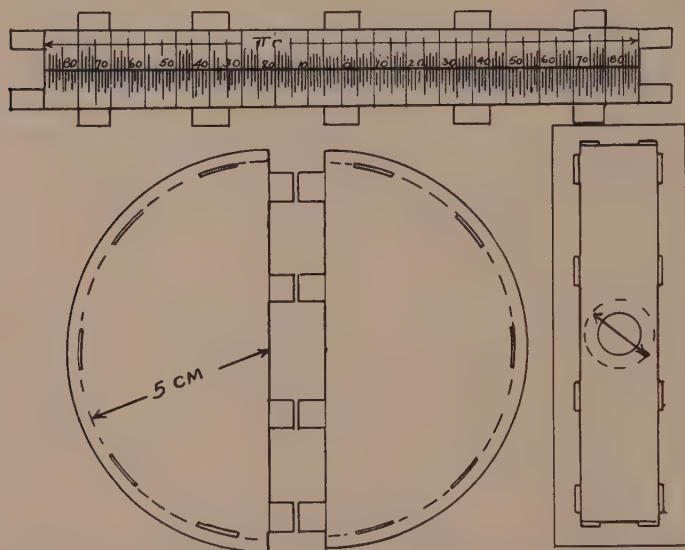


FIG. 4. Diagram showing constituent parts of the semicircular celluloid protractor, 2E goniometer, illustrated in figure 5. One-half natural size.

The following determinations were made of the optic angles displayed by the suite of sections available to the writer.<sup>3</sup>

<i>Mineral</i>	<i>Quality of optic figure</i>	<i>Temperature</i>	<i>2E</i>
Chrysoberyl	fair	28°C.	134°
Cerussite	good	27°	19°
Cerussite	good	28°	19°
Barite	good	27°	70°
Gypsum	good	27°	92°
Struvite	good	28°	67°
Adularia	fair	27°	119°
Cordierite	good	27°	75°
Mica (lepidolite ?)	very good	27°	78°
Axinite	poor	27°	141°(?)
Sanidine	good	27°	13°
Cane sugar	good	27°	86°
Potassium bichromate	good	28°	108°

<sup>3</sup> The writer is indebted to Mr. W. F. Wrath for making these measurements.

These measurements appear to be close enough to the usually accepted values of the substances represented to be at least approximately correct. In the hope of gaining a more precise check upon the reliability of the instrument, the writer sent it to Dr. Stanley A. Tyler at the University of Wisconsin. He checked measurements made by two observers with the 2E goniometer against universal stage determinations, as follows:—

<i>Mineral</i>	<i>2E absolute</i>	<i>2E goniometer S. A. T.</i>	<i>2E goniometer R. W. M.</i>
Barite (from England)	63°18'	62°30'	64°
Muscovite (Mitchell Co., N. C.)	61°17'	61°	60°

In spite of lack of complete accuracy, this 2E goniometer is evidently accurate enough to be useful.

#### PROJECTION UPON A HEMISPHERE

The apparent success of the 2E goniometer led to the construction of a translucent hemisphere over polaroid mounted upon an accessory stage. Such an apparatus was first demonstrated at the meetings of the Geological Society of America in Cincinnati, December 30, 1936, incidental to an explanation of the 2E goniometer.<sup>4</sup> The model shown at that time was attached to the arm of the microscope, and made so that it could be swung over and away from the stage of the microscope. The instrument was equipped with celluloid hemispheres of two sizes, one made from one-half a table-tennis ball, and another about 4 cm. in diameter. Each hemisphere was provided with a protractor over the zenith in a vertical plane, and another around the edge in the horizontal plane. With the aid of these protractors the position of emergence of the eyes of optic figures could be located by both latitude and longitude. The small hemisphere yielded the more brilliant figure, but the larger scales were easier to read. By these means it appeared possible to read rapidly the relative orientation of grains in a rock section; and certainly it was obvious that optic figures may be beautifully demonstrated.

Professor D. J. Fisher<sup>5</sup> has applied these ideas to the equipment of a universal stage with direct projection of optic figures upon a half table-tennis ball, attaining a much greater degree of accuracy than is possible without a universal stage. Professor Fisher's apparatus is far more accurate than that of the present writer, it serves more inclusive purposes, and of course it is designed for, and useful only in connection with a universal stage.

<sup>4</sup> *Proc. Geol. Soc. America* for 1936, p. 50.

<sup>5</sup> Demonstrated at the meetings of the Geol. Soc. of America, Washington, D. C., December, 1937.



*A new direct projection stage*

Inasmuch as many petrographic laboratories do not possess a universal stage, the writer has designed and exhibited<sup>6</sup> an improved stage for the direct projection of optic figures. This stage is made attachable to the substage frame of any standard petrographic microscope. It includes a vertical bearing about which a polaroid holder is rotated, and upon which it may be adjusted with any convenient clearance above the regular stage. Above the polaroid plate is placed a translucent celluloid hemisphere with vertical and horizontal angular scales. This hemisphere is specially made 5 cm. in diameter. Mineral sections may be placed upon

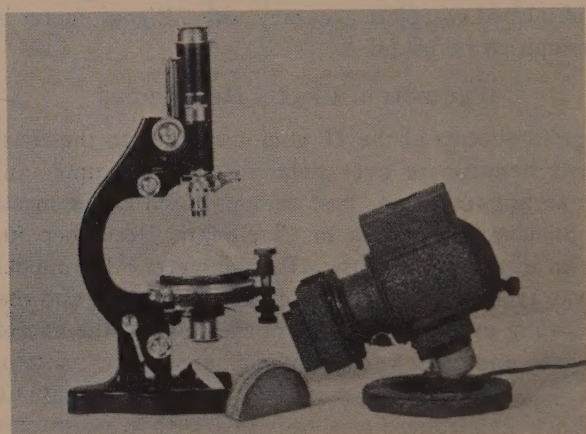


FIG. 5. A new accessory stage for the direct projection of optic figures, mounted as for use. A celluloid protractor 2E goniometer stands beside the microscope.

the stage of the microscope and the accessory stage may be operated above it, each stage being manipulated independently. In the case of research models of microscopes there is room enough beneath the objective for the accessory stage without removing the barrel of the microscope from its mounting. Accordingly, an observer may explore a rock section with a low power objective, using Johannsen's<sup>7</sup> micro-ball device, for grains yielding optic figures, and after centering such a grain, he may place over it the accessory stage for further observation of the optical figure and measurement of its orientation or the angle 2E. The illustration (Fig. 5) shows the improved direct projection accessory stage mounted upon a microscope, and beside it a model of the simple 2E

<sup>6</sup> Annual meetings of the Geological Society of America. Washington, D. C., 1937.

<sup>7</sup> Albert Johannsen, *Jour. Geology*, vol. 21, pp. 96-98, 1913.



goniometer. The goniometer has in its base a sheet of polaroid which is placed so that when the main vertical plane of the goniometer is in the  $45^\circ$  position over a suitable mineral section, the polaroid analyzer is crossed with reference to the substage polarizer. In the case of the accessory stage, the polaroid analyzer is fixed in position such that when the accessory stage is centered with respect to the microscope stage, the analyzer is crossed with respect to the polarizer. In the mounting of this stage it is necessary to lower the substage equipment until the attachments are firmly screwed into place, and in the operation of the stage success depends upon such an adjustment of the illumination and placing of the converging lens that a sharp and brilliant optic figure appears upon the celluloid hemisphere. Ordinarily it is not necessary to darken the room for the use of this stage, but for demonstration purposes of course it is desirable.

## NOMINATIONS FOR OFFICERS OF THE MINERALOGICAL SOCIETY OF AMERICA FOR 1939

The Council has nominated the following as officers of *The Mineralogical Society of America* for the year 1939:

PRESIDENT: Max N. Short, University of Arizona, Tucson, Arizona.

VICE-PRESIDENT: Burnham S. Colburn, Greystone Court, Biltmore, North Carolina.

SECRETARY: Paul F. Kerr, Columbia University, New York, New York.

TREASURER: Waldemar T. Schaller, U. S. Geological Survey, Washington, D. C.

EDITOR: Walter F. Hunt, University of Michigan, Ann Arbor, Michigan.

COUNCILLOR (1939-1942): Carl Tolman, Washington University, St. Louis, Missouri.

The nineteenth annual meeting of the Society will be held at the Waldorf-Astoria Hotel, New York City, December 28-30, 1938, in connection with the 50th Anniversary meeting of the Geological Society of America.

Members of the Society who are planning to present papers at the scientific sessions of the annual meeting should notify the Secretary as soon as possible in order to receive the proper blanks for their abstracts. All abstracts should be in the Secretary's office by November 20th.

An advance announcement of the annual meeting will be distributed to members of the Society with the ballot for officers, in the middle of October. The final program of the meeting, containing the schedule of papers, abstracts, and other information regarding the annual luncheon and the presentation of the Roebling Medal, will be sent to each member with the December issue of *The American Mineralogist*. Specific information regarding the annual meeting may be obtained from the Secretary's office.

PAUL F. KERR, *Secretary*

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## CORRECTIONS

DUNCAN MCCONNELL

Mr. T. Deans, of Cambridge University, has kindly called attention to an error which appeared in the work of Gruner and McConnell<sup>1</sup> and which was repeated in the work on apatites by McConnell.<sup>2</sup> On page 7, at the bottom, where the statistical distribution of the ions in francolite is given, the value for OH should be 1.000, not 0.100. This change necessitates an adjustment in the number of oxygen ions. The 24 O-positions contain 22.832 O+1.000 OH+1.68 F. The distribution of the ions in the Ca-, P-, and F-positions is not altered. This change, furthermore, slightly alters the value for the molecular weight and, consequently, the theoretical density. The theoretical density is 1.154, not 1.151 as given.

On the basis of an analysis by Pisani, reported by Lacroix,<sup>3</sup> the specimen of dahllite from Mouillac, Quercy, France, is described as a carbonate hydroxy-apatite. A new and complete analysis<sup>4</sup> of a sample from the same locality and supposedly identical with the material analyzed by Pisani, has revealed that the mineral is a carbonate oxy-apatite because it is deficient in water as well as fluorine.

These two corrections do not alter the general conclusions regarding isomorphism which were based upon either of these minerals.

<sup>1</sup> *Zeits. Krist.*, vol. 97, pp. 208-215, 1937.

<sup>2</sup> *Am. Mineral.*, vol. 23, pp. 1-19, 1938.

<sup>3</sup> *Compt. Rend.*, vol. 150, p. 1390, 1910.

<sup>4</sup> *Am. Jour. Sci.*, vol. 36, in press, 1938.